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Distribution network planning integrating charging stations of electric vehicle with V2G

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ABSTRACT

Accompanied by the popularization of EVs, the planning of electric vehicle (EV) charging stations becomes an important concern of distribution network planning. In this paper, the load density method is introduced to determine the optimal capacity of the EV charging stations in the areas to be planned, and the difference between 1 and the weight coefficients obtained by the analytic hierarchy process (AHP) method is used to calculate the cost coefficients of the charging station. The objective function of the optimal distribution network planning model should be the minimal cost of the fixed investments, the operational costs and the maintenance costs including the substations, charging stations and feeders. In this model, the effect of vehicle-to-grid (V2G) is considered, i.e., the EV is respectively treated as both the load and the source. Moreover, the electricity price volatility has been taken into consideration. In this case, EV owners can be guided to charge and discharge EV orderly. The ordinal optimization approach is applied to get the best solution. The results of the case study based on IEEE 54 nodes model show the feasibility and effectiveness of the proposed model.

Introduction

Developing electric vehicles (EVs) is an effective measure to reduce our dependence on fossil fuels, and the massive popularity of EVs is recognized as the trend of future. To promote the benign development of EVs and the EV charging facilities in power network, future distribution network planning should take both the EVs charging demand and discharging capacity into consideration. Therefore, besides meeting the demands of the conventional distribution network planning [1–3], the planning work of distribution network integrated with EV charging stations requires solutions to additional technical issues, including capacity planning of EV charging stations, site selection of charging stations, planning of substations and feeders in power network containing EV charging stations, etc. [4–7].

Presently, the EV's impacts on the distribution planning have been presented in many references. In [8], the optimal siting and sizing of EV charging stations are studied from the three aspects: convenience, transport traffic and land expropriation cost. Charging facility planning is constructed in three stages and the optimized model of charging mode choices according to the different charging methods are also proposed in [9]. In [10], the method in view of the geographical factors and service radius of EV charging station, which fully takes the influence of the battery on the power grid into account, is presented for the purpose of establishing the model of EV charging station in view of site and capacity. In [11], the operation mode of "centralized charging, unified distribution" is introduced, with which the centralized charging station model is built to decide the capacity and site from the viewpoint of lines' transmission capacity and land price. In [12], the convenience and economics are both considered for optimizing the layout of EV charging station and modeling the radial distribution system planning. However, all the above references treat the EV as only loads when evaluating the problems of siting, sizing and the effect of EV to distribution networks. They do not reflect the main characteristic of EV in terms of both sources and loads. Considering the ability of EV charging, several typical schemes of EV connected to the grid are analyzed [13]. However, this reference did not analyze the impacts on the entire distribution network planning in terms of the randomness of connected into the power system. In order to clarify the above problem, the effect of the EV as the load and the source on the distribution system is comprehensively analyzed respectively in this paper. Furthermore, the optimal planning

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model under the constraint of radial structure is established in line with the V2G characteristics of EV.

Analysis of the impacts on the distribution network planning due to V2G

The V2G technology can relieve the problems of low grid efficiency and renewable energy fluctuation, and also bring EV owners profits [14]. Moreover, experts believe that V2G technology will lead to a big change to the traditional power network operation. V2G allows EVs to feed the energy back to the grid. During the period of peak load, energy stored in EVs will be fed back to the grid. Instead, EVs can store extra power energy during off-peak periods. Large scale of EVs connected to the power grid will bring great changes in many aspects, for instance, original distribution power flow, network loss and power supply reliability. Therefore, new requirements for distribution network structure arise. In this paper, V2G features are taken into consideration when planning the distribution network integrating EV charging stations.

Sizing of charging station

The load density forecasting method [15] is adopted to determine the capacity of charging station. Firstly, the district to be planned should be divided into N functional regions according to the convention and the reality. The load density indices in this paper are selected from the residential load density by practice, of which the predicted load $S_i(i = 1, 2\ldots, N)$ of each region and the formative total load S_{total} are obtained using the load density method. The convenience of EV's charging should be taken into account when designing the rated capacity of a charge station. The total sum N_{car} of EV will be available by means of the statistics of the department of transportation. The formula of deciding the capacity of EV charging station is given by:

$$S_{csi} = k \times N_{car} \times P_{charge} \times \frac{S_i}{S_{total}} \tag{1}$$

where k denotes the charging simultaneity of EVs, that is, the ratio of charging EVs to the total EV amount in statistical probability. And P_{charge} denotes the average power of charging.

Determination of the weight coefficients of candidate EV charging stations

Analytic hierarchy process (AHP) [16] is a kind of practical multi-objective decision-making analysis method, which combines qualitative analysis with quantitative analysis [17]. In this paper, the weight coefficients of candidate addresses are determined by using AHP [8]. The difference of 1 and the weight coefficient is taken as the cost weight coefficient of the EV charging station in the planning model. The planning of the EV charging station should not only consider the economic benefits, but the social ones, the environmental ones and others. It is a multi-criteria decision problem that can be solved by AHP method. The steps of determining the weight coefficients of candidate EV charging stations are as follows [18].

The first step: Establish the hierarchical structure of the influence factors, that is, construct the quantitative index system based on the influence factors of the layout of the EV charging station. The hierarchical structure of the weight coefficients of candidate charging stations in this paper is shown in Fig. 1. Where, it is supposed that there are only two candidate EV charging stations to be chosen.

The second step: Construct the judgment matrix. The judgment matrixes of the criterion layer and the measures layer are established individually. For the purpose of implementation, the judgment of the importance of the elements can be assigned based on the AHP multiplicative 1–9 scale method. By this means, the judgment matrix can be established. In view of importance ranking, the social benefits should be the foremost concern. The second will be the environmental benefits and then the economic benefits.

The third step: Hierarchy single ranking and its uniformity inspection. In this paper, every layer is firstly ordered by using the sum method, and then the result is utilized to get the total ordering. In the actual application, the consistency of the judgment matrix needs to be examined, in which the specific operation method can be obtained in [19].

The fourth step: Hierarchy general ranking and its uniformity inspection. The results of hierarchy single ranking are used to form the results of hierarchy general ranking from the top to the bottom. Finally, the uniformity of the hierarchy general ranking results should be examined.

The fifth step: Result analysis. In every candidate scheme, the hierarchy general ranking results are the weight coefficients of candidate addresses. They will be the important basis for selecting the ultimate decision scheme. The difference of 1 and the calculated weight coefficient is treated as the annual investment cost coefficient of the EV charging station, which can directly affect the cost of the distribution network planning.

Planning model of the radial distribution network containing eV charging station

Objective function

The optimal solution of the objective function is the minimum cost that includes C_1, the annual investment cost, C_2, the annual maintenance depreciation cost, and C_3, the comprehensive annual operational cost of the transformer substation and the feeder of distribution network and EV charging station, as given below:

$$\min(Cost = C_1 + C_2 + C_3) \tag{2}$$

where,

$$C_1 = \sum_{i=1}^{m_{sub}} \beta_{sub} A_{si} R_i + \sum_{i=1}^{m_{lin}} \beta_{lin} A_{li} R_i + \sum_{i=1}^{m_{cs}} \beta_{cs}(1-\lambda_i) A_{csi} R_i \tag{3}$$

$$C_2 = \alpha C_1 \tag{4}$$

$$C_3 = \mu_1 \sum_{i=1}^{n_l} c_i \tau_{\max} \Delta P_i + \mu_2 \sum_{i=1}^{n_l} (c_i' - c_i) \tau_{\max}' \Delta P_i' + \mu_2 \sum_{i=1}^{n_l} 0.7 \times (c_i' - c_i) \tau_{\max}' P_{charge} \tag{5}$$

$$\beta = \frac{r(1+r)^{n_1}}{(1+r)^{n_1} - 1} (1+r)^{n_2} \tag{6}$$

The definition of the parameters in the formula from (2) to (6) is shown in Table 1.

Constraints

The constraint conditions of the radial distribution network planning and the charging station of EV are taken into account. Besides satisfying regular constraints of charging station of EV, the planning model also needs to meet the requirement of the restriction of capacity and the voltage drop due to charging station to ensure the safe operation of the power grid [6,20].