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RESEARCH ARTICLE

A Disposal Strategy for Tight Power Balance Considering Electric Vehicle Charging Station Providing Flexible Ramping Capacity

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ABSTRACT To tackle the high stochastic characteristic of renewable energy resources, such as wind power, sufficient flexibility is of great necessity to the security and economic operation of power systems. With increasing wind power penetration in the power system, the flexibility demand and the possibility of wind spillage are on the rise. Under the tight power balance state, the flexibility solely provided by thermal units will reduce the system flexibility, resulting in load shedding. It is imperative to utilize flexible resources to reduce wind spillage and load shedding. To address the above problems, the power system flexibility supply and demand model and electric vehicle (EV) charging stations operation model are first constructed in this paper. On this basis, a disposal strategy for tight power balance with EV charging stations providing flexible ramping capacity is established. Finally, numerical simulations are conducted on the modified IEEE 118-bus system. Results show that the integration of EV charging stations reduces the operation cost of the system by 11.72%, wind spillage by 17.88%, load shedding by 59.42% and provides flexibility to the system.

INDEX TERMS Tight power balance, electric vehicle charging station, flexible ramping capacity, wind power, wind spillage, load shedding.

I. INTRODUCTION

Increasing the penetration of renewable energy sources integrated into the power systems can help to solve the problems about fossil energy depletion and environmental pollution [1], [2], [3]. However, the system is required to promote its flexibility to cope with the variability of the net load (system load minus renewable energy output) [4], [5] due to the uncertainty of renewable energy sources such as wind power. With the increase in penetration of renewable energy and system load, the problem of the insufficient flexibility of the system will become extremely serious.

Traditionally, the demand for flexibility was met mainly by thermal units. California Independent System Operator (CAISO) and Midcontinent Independent System Operator (MISO) have designed market-based flexible ramping products, mainly provided by thermal units, to improve the flexibility of the system [6]. Cui et al. [7] developed a power system multi-timescale dispatch model considering wind power ramping product, which can effectively reduce the cost of flexible ramping product provided by conventional units. Alizadeh [8] investigated a multistage multiresolution day-ahead robust unit commitment considering flexible ramp reserves provided by conventional generation units. Naghdalian et al. [9] proposed a stochastic network constrained unit commitment (NCUC) model, which satisfied the required flexible ramp and spinning reserves through the optimal schedule of generation units. A unified framework for defining and measuring the system flexibility was proposed in [10]. Under this framework, a flexibility metric was proposed and applied to real-time operation with online units providing flexibility. Wu et al. [11] designed a novel routine to eficiently

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solve the non-convex risk-limiting economic dispatch problem with flexible ramping products provided by generators. Wang et al. [12] conducted an evaluation analysis for the unit commitment-based flexible ramping real-time market with thermal units providing flexible ramp.

Although references [6], [7], [8], [9], [10], [11], and [12] utilize thermal units to provide most of the flexibility, they ignore the reduction of thermal units' operating life and regulation capacity [13], which resulted from frequent operation of thermal units starting-up, shutting-down and ramping up/down. Fortunately, flexible resources such as EV charging stations [14], responsive loads [15], energy storages [16], [17], both can provide flexibility to the system and reduce the burden of thermal units. Many studies mainly focus on EVs among these resources to provide the flexibility, reduce carbon emission and protect the environment [18]. Zhang et al. [19] estimated EV flexibility and proposed a new market mechanism for distribution system to incentive dispatchable EVs to provide flexible ramping services. Lu et al. [20] exploited the temporal flexibility of EV aggregators to mitigate the prediction uncertainty in the distribution system. Zhang et al. [21] evaluated the impact of electric vehicles on power system reliability and flexibility.

Currently, the system probably suffers from the short-term peak load in some specific situation. Under this circumstance, the balance of power supply and demand are in tight conditions and we define this issue as the tight power balance problem. This extra issue may influence the flexibility enhancement of the systems [14], [15], [16], [17], [18], [19], [20], [21]. In addition, the tight power balance state will further limit the ability of the system to provide flexibility. Once the system is unable to meet the demand for flexibility, the result will be wind spillage and load shedding, which seriously influences the security and economic operation of the power system [22], [23]. This motivates us to propose a disposal strategy for tight power balance considering electric vehicle charging station providing flexible ramping capacity to tackle this issue.

The main contributions of this paper are as follows:

1) To address the tight power balance problem in power systems with high wind power penetration, a disposal strategy with EV charging stations providing flexible ramping capacity is proposed to reduce load shedding and wind spillage.

2) In analysis of the tight power balance, the amount of load shedding is used to quantify the severity level of tight power balance. EV charging stations are integrated to the grid to provide flexibility and reduce load shedding.

The remainder of this paper is organized as follows. In Section II, the problem formulation is introduced. In Section III, the operation of electric vehicle charging stations is modeled. In Section IV, the disposal strategy for tight power balance is established. Numerical simulation results are presented and discussed in Section V. Section VI concludes the paper.

II. PROBLEM FORMULATION

The installed capacity of generation units is insufficient to meet the load demand under the tight power balance state. As the penetration of wind power continues to rise, so does the demand for flexibility. The demand for flexibility solely provided by thermal units would limit the range of their output, which influences the capability of the system to maintain the balance of generation and load. Therefore, the problem of the insufficient system flexibility is further magnified, necessitating the adoption of wind spillage and load shedding to maintain the balance of the power supply and demand.

To address the tight power balance problem in the high wind power penetration to power system, this paper establishes a disposal strategy for tight power balance considering EV charging station providing flexible ramping capacity. The integration of EV charging stations to the system can reduce the system wind spillage and load shedding, enhance the system flexibility, and guarantee the security and economic operation of the power system.

An EV charging station can be seen as an aggregator to integrate EVs and operate interactively with the grid [24]. In this paper, EV charging stations are aggregators that participate in the energy, reserve, and flexible ramp markets on behalf of EV owners. EVs can operate in both vehicle-to-grid (V2G) and grid-to-vehicle (G2V) modes, which can provide flexibility to the system. However, the primary mission of EVs is transportation, and therefore the flexibility offered by EVs is limited by constraints associated with the behavior of each EV owner.

In this paper, the time scale involved in the tight power balance disposal is 4 h with a resolution time scale of 15 min. In a

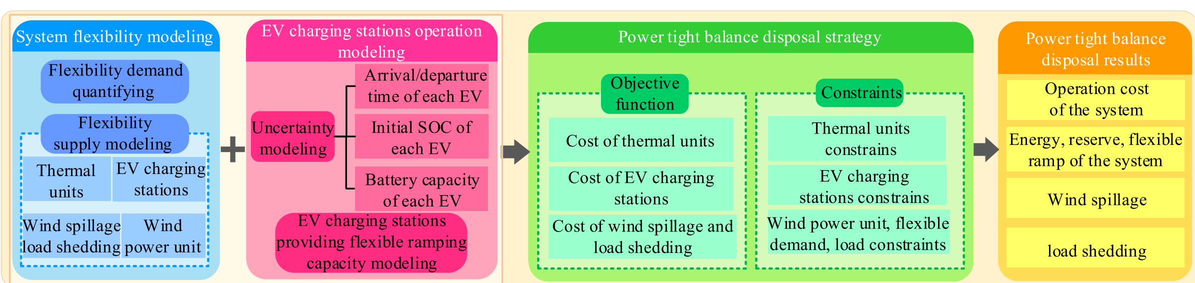

FIGURE 1. The flow chart for tight power balance disposal.

unit commitment problem, the start-up and shut-down schedule of the units need to be determined [25]. However, in this paper, with a known unit start-up and shut-down schedule, the output of each unit is determined by optimally allocating the total load to satisfy the operation constraints. The tight power balance disposal process is shown in FIGURE 1. The detailed calculation processes are described as follows:

The flow chart for tight power balance disposal.

Step 1: Simulate the operation of EV charging stations based on the uncertainty modeling of EV charging stations and the modeling of EV charging stations providing flexible ramping capacity.

Step 2: Quantify the flexibility demand of the system. A tight power balance disposal strategy is constructed including EV charging stations, thermal and wind units, which minimizes the total operation cost of the system while satisfy the operation constraints.

Step 3: Obtain the operation cost of the system, energy, reserve, flexible ramp of the system, wind spillage, and load shedding by solving the tight power balance disposal model.

III. MODELING OF ELECTRIC VEHICLE CHARGING STATION OPERATION

Before constructing the tight power balance disposal strategy, the operation of EV charging stations is simulated via the uncertainty of EV charging stations and the modeling of EV charging stations providing flexible ramping capacity.

A. THE UNCERTAINTY MODELING OF EV CHARGING STATIONS

Uncertainty of the EV charging stations arises from the arrival/departure time, the initial state of charge (SOC), and the battery capacity of EVs. To model the uncertainty of EV behavior, truncated Gaussian distribution is widely used to model the arrival/departure time and initial SOC of EVs [18], [26]. The truncated Gaussian distribution is a type of Gaussian distribution and also a truncated distribution, which can restrict the range of random variable [27]. Therefore, we generate three sets of random numbers based on truncated Gaussian distribution to simulate the arrival/departure time, and initial SOC of EVs. The generation process reaches equilibrium until satisfying the parking space constraint at the charging station.

In addition, the uncertainty in the available battery capacity of EVs in charging stations, the 24 battery classes used for different types of EVs, and the probability distribution of the model, are presented in [18]. The uncertainty modeling of EV charging stations can be found in [14].

B. THE MODELING OF EV CHARGING STATIONS PROVIDING FLEXIBLE RAMPING CAPACITY

EV charging stations are similar to energy storages and can provide up flexible ramp when in the vehicle-to-grid (V2G) mode, which is equivalent to the discharging state of energy storages, and provide down flexible ramp when in the grid-to-vehicle (G2V) mode, which is equivalent to the charging state of energy storages. The flexible ramping capacity provided by EV charging stations is constrained by the charging and discharging rate of EVs, the capacity and SOE of EV charging stations, and the contract between the EV owners and the grid.

The energy, reserve and flexible ramp of charging stations are limited by the aggregated number of EVs in charging station and their charging/discharging rates as shown in (1)-(3).

$$p_{pl,t}^{En,PL2G} + FRU_{pl,t}^{PL} + SP_{pl,t}^{PL} + NS_{pl,t}^{PL} + REG_{pl,t}^{PL\_up} + REP_{pl,t}^{PL} \leq \gamma^{disch\arg e} N_{pl,t}^{PL,Sc} u_{pl,t}^{PL2G} \tag{1}$$

$$p_{pl,t}^{En,G2PL} + FRD_{pl,t}^{PL} + REG_{pl,t}^{PL\_dn} \leq \gamma^{ch\arg e} N_{pl,t}^{PL,Sc} u_{pl,t}^{G2PL} \tag{2}$$

$$u_{pl,t}^{PL2G} + u_{pl,t}^{G2PL} \leq 1 \tag{3}$$

The aggregated SOE of charging stations is modeled by the remaining SOE from previous time, the SOE due to arrival/departure of EVs, energy, reserve and flexible ramp as in (4).

$$\begin{aligned} SOE_{pl,t}^{PL} = {} & SOE_{pl,t-1}^{PL} + SOE_{pl,t}^{arv} - SOE_{pl,t}^{dep} \\ & + \eta_{Ch}^{PL}(p_{pl,t}^{En,G2PL} + FRD_{pl,t}^{PL} + REG_{pl,t}^{PL\_dn}) \\ & - {}^{1}\!/\eta_{Dch}^{PL}(p_{pl,t}^{En,PL2G} + FRU_{pl,t}^{PL} + SP_{pl,t}^{PL} \\ & + NS_{pl,t}^{PL} + REG_{pl,t}^{PL\_up} + REP_{pl,t}^{PL}) \end{aligned} \tag{4}$$

Assuming a contract between the charging station and the EV owner to allow the charging station to use the EV's energy in vehicle-to-grid (V2G) mode [18], [28]. The charging station should then aggregate the required SOC assigned in the contract for each time period to limit the maximum power exchange with the grid as shown in (5).

$$p_{pl,t}^{En,PL2G} + FRU_{pl,t}^{PL} + SP_{pl,t}^{PL} + NS_{pl,t}^{PL} + REG_{pl,t}^{PL\_up} + REP_{pl,t}^{PL} \leq \psi_{pl,t} SOE_{pl,t}^{PL,Sc} \tag{5}$$

The minimum and maximum limits of EVs' SOC are formulated in (6). The SOC and SOE limits of charging stations can be represented in (7)-(8).

$$soc_{n}^{EV,\min} \leq soc_{n,t}^{EV} \leq soc_{n}^{EV,\max} \tag{6}$$

$$\underbrace{\sum_{n} soc_{n}^{EV,\min}}_{SOC_{pl}^{\min}} \leq SOC_{pl,t}^{PL} \leq \underbrace{\sum_{n} soc_{n}^{EV,\max}}_{SOC_{pl}^{\max}} \tag{7}$$

$$SOC_{pl}^{\min} Cap_{pl,t}^{PL,Sc} \leq SOE_{pl,t}^{PL} \leq SOC_{pl}^{\max} Cap_{pl,t}^{PL,Sc} \tag{8}$$

IV. DISPOSAL STRATEGY FOR TIGHT POWER BALANCE

The source of the demand for flexibility is the stochastic characteristic of the net load. In this paper, we construct the upper and lower limits of the net load fluctuation and then obtain the demand for flexibility of the system. By subtracting the net load of the previous period from the next period, the positive result represents the up flexible ramping demand; the negative result represents the down flexible ramping demand. The specific model is given in this section.

Integrating EV charging station, a flexible resource, in the tight power balance disposal under a 4-hour time scale, the following are the objective function and constraints of the tight power balance disposal strategy.

A. OBJECTIVE FUNCTION

The objective function minimizes the total operation cost of the system including thermal units' operation costs, conventional auxiliary service reserve costs, flexible ramping capacity costs, EV charging stations discharging costs, and penalty costs for the system wind spillage and load shedding as shown in (9)-(12).

$$\min C = C_1 + C_2 + C_3 \tag{9}$$

$$\begin{aligned} C_1 = &\sum_{t=1}^{N_T}\sum_{i=1}^{N_I}[MPC_{i,t}(p_{i,t}) + \lambda_{i,t}^{G\_sp} SP_{i,t}^{G} \\ &+ \lambda_{i,t}^{G\_ns} NS_{i,t}^{G} + \lambda_{i,t}^{G\_reg} REG_{i,t}^{G\_up} \\ &+ \lambda_{i,t}^{G\_reg} REG_{i,t}^{G\_dn} + \lambda_{i,t}^{G\_rep} REP_{i,t}^{G} \\ &+ \lambda_{i,t}^{G\_up} FRU_{i,t}^{G} + \lambda_{i,t}^{G\_dn} FRD_{i,t}^{G}] \end{aligned} \tag{10}$$

$$\begin{aligned} C_2 = &\sum_{t=1}^{N_T}\sum_{pl=1}^{N_{PL}}[\lambda_{pl,t}^{PL\_Eng} p_{pl,t}^{En,PL2G} + \lambda_{pl,t}^{PL\_sp} SP_{pl,t}^{PL} \\ &+ \lambda_{pl,t}^{PL\_ns} NS_{pl,t}^{PL} + \lambda_{pl,t}^{PL\_reg} REG_{pl,t}^{PL\_up} \\ &+ \lambda_{pl,t}^{PL\_reg} REG_{pl,t}^{PL\_dn} + \lambda_{pl,t}^{PL\_rep} REP_{pl,t}^{PL} \\ &+ \lambda_{pl,t}^{PL\_up} FRU_{pl,t}^{PL} + \lambda_{pl,t}^{PL\_dn} FRD_{pl,t}^{PL}] \end{aligned} \tag{11}$$

$$C_3 = \sum_{t=1}^{N_T}[\sum_{w=1}^{N_W} \lambda_{w,t}^{WT\_spill} P_{w,t}^{WTspill} + \sum_{j=1}^{N_J} \lambda_{j,t}^{LS} LS_{j,t}] \tag{12}$$

Equation (10) represents the cost of thermal units; equation (11) represents the cost of EV charging stations; equation (12) represents the cost of wind spillage and load shedding.

B. CONSTRAINTS

1) THERMAL UNITS CONSTRAINTS

Up and down flexible ramping capacity of thermal units' constraints, which ensures the amount of up and down flexible ramp does not exceed thermal units' ramping limits, are shown in (13)-(14).

$$FRU_{i,t}^{G} + SP_{i,t}^{G} + NS_{i,t}^{G} + REG_{i,t}^{G\_up} + REP_{i,t}^{G} \le R_i^{up}\tau \tag{13}$$

$$FRD_{i,t}^{G} + REG_{i,t}^{G\_dn} \le R_i^{dn}\tau \tag{14}$$

Maximum and minimum active power of thermal units' constraints considering output, reserve and flexible ramp of thermal units are formulated by (15)-(16).

$$p_{i,t} + FRU_{i,t}^{G} + SP_{i,t}^{G} + NS_{i,t}^{G} + REG_{i,t}^{G\_up} + REP_{i,t}^{G} \le p_i^{\max} \tag{15}$$

$$p_{i,t} - FRD_{i,t}^{G} - REG_{i,t}^{G\_dn} \ge p_i^{\min} \tag{16}$$

2) EV CHARGING STATIONS CONSTRAINTS

The EV charging stations constraints are given in constraints (1)-(8) therefore not repeated here.

3) WIND POWER UNIT, SYSTEM FLEXIBILITY AND LOAD DEMAND CONSTRAINTS

Maximum and minimum active power of wind power unit and the system wind spillage constraints can be formulated by (17)-(18).

$$0 \le p_{w,t}^{WT} \le p_{w,t}^{WT\max} \tag{17}$$

$$P_{w,t}^{WTspill} = p_{w,t}^{WT\max} - p_{w,t}^{WT} \tag{18}$$

Wind power unit providing flexible ramping capacity constraints can be shown in (19).

$$\begin{cases} FRU_{w,t}^{WT} = \max(p_{w,t+1}^{WT} - p_{w,t}^{WT}, 0) \\ FRD_{w,t}^{WT} = \max(p_{w,t}^{WT} - p_{w,t+1}^{WT}, 0) \end{cases} \tag{19}$$

Modeling of system demand for flexibility, which is discussed in FIGURE 2, can be shown in (20)-(21). The fluctuation coefficient κ is defined as the maximum error rate between the predicted and actual data [16].

$$\begin{cases} P_t^{NL\max} = (1+\kappa)P_t^{NL} \\ P_t^{NL\min} = (1-\kappa)P_t^{NL} \end{cases} \tag{20}$$

$$\begin{cases} FRUN_t = \max(0, P_t^{NL\max} - P_{t-1}^{NL}) \\ FRDN_t = \max(0, P_{t-1}^{NL} - P_t^{NL\min}) \end{cases} \tag{21}$$

In extreme cases, flexibility can be provided to the system by wind spillage and load shedding as shown in (22), but this will result in an increase in operation costs. System up and down flexible ramping demand constraints can be shown in (22)-(24).

$$\begin{cases} FRU_t^{LS} = \sum_{j\in N_J} LS_{j,t} \\ FRD_t^{WTspill} = \sum_{w\in N_W} P_{w,t}^{WTspill} \end{cases} \tag{22}$$

$$\sum_{i=1}^{N_I} FRU_{i,t}^{G} + \sum_{w=1}^{N_{WT}} FRU_{w,t}^{WT} + \sum_{pl=1}^{N_{PL}} FRU_{pl,t}^{PL} + FRU_t^{LS} \ge FRUN_t \tag{23}$$

$$\sum_{i=1}^{N_I} FRD_{i,t}^{G} + \sum_{w=1}^{N_{WT}} FRD_{w,t}^{WT} + \sum_{pl=1}^{N_{PL}} FRD_{pl,t}^{PL} + FRD_t^{WTspill} \ge FRDN_t \tag{24}$$

System power balance constraint and transmission line limit constraint are shown in (25)-(26).

$$\sum_{i=1}^{N_I} p_{i,t} + \sum_{w=1}^{N_{WT}} p_{w,t}^{WT} + \sum_{pl=1}^{N_{PL}} (p_{pl,t}^{En,PL2G} - p_{pl,t}^{En,G2PL}) = \sum_{j=1}^{N_J}(D_{j,t} - LS_{j,t}) \tag{25}$$

$$-P_l^{L\max} \le \sum_{i=1}^{N_I} G_{l-i}p_{i,t} + \sum_{w=1}^{N_{WT}} G_{l-w}p_{w,t}^{WT} + \sum_{pl=1}^{N_{PL}} G_{l-pl}(p_{pl,t}^{En,PL2G} - p_{pl,t}^{En,G2PL}) - \sum_{j=1}^{N_J} G_{l-j}(D_{j,t} - LS_{j,t}) \le P_l^{L\max} \quad (26)$$

V. NUMERICAL EXAMPLE

In this paper, the numerical example is carried out based on the modified IEEE 118-bus system [7], which has 54 thermal units, 186 branches and 91 load buses. The wind power unit is connected at bus 43 and two EV charging stations with 135,000 charging spaces each located at buses 58 and 72, respectively. Wind and load data are taken from [14]. The reserve capacity and the offered costs for reserve of generation units are extracted from [26], and the penalty cost of wind spillage and load shedding are 40 \$/MWh and 200 \$/MWh, respectively [14]. The aggregated number of EVs, SOE and the capacity of EVs available in charging stations are obtained by modeling each EV charging station based on the uncertainty of EVs. The parameters of EV charging stations are shown in TABLE 1, which are extracted from [14]. The numerical simulation of the proposed tight power balance disposal strategy is implemented by using MATLAB R2018a and YALMIP toolbox, and the validity of the proposed strategy is verified by using ILOG CPLEX 12.8.

TABLE 1. Electric vehicle charging station parameters [14].

γ^{charge} (kW/h)	$\gamma^{discharge}$ (kW/h)	$\eta^{PL}_{Ch/Dch}$ (%)	ψ_{pl} (%)	$SOC_{pl}^{\min}$ (%)	$SOC_{pl}^{\max}$ (%)
22	22	90	40	30	90

A. THE IMPACT OF EV CHARGING STATIONS

In order to show the effectiveness of our proposed method, two cases are investigated as follows:

Case 1: Considering thermal units and wind power unit to participate in the tight power balance disposal, without considering EV charging stations.

Case 2: Considering thermal units, wind power unit and electric vehicle charging stations to participate in the tight power balance disposal.

The results of operation cost, wind spillage, load shedding, thermal unit ramp and saving of thermal units' ramp for the tight power balance disposal under the above two cases are shown in TABLE 2. The saving of thermal units' ramp refers to the amount of flexible ramp that EV charging stations provide to the system.

The comparison is to show how EV charging stations improve the tight power balance disposal level by reducing system operation cost, wind spillage, load shedding, and providing flexibility to the system. According to TABLE 2, the economy and flexibility of the power system are both improved after the integration of EV charging stations. Moreover, the operation cost of the system is reduced by 11.72%, wind spillage is reduced by 17.88%, and load shedding is reduced by 59.42% in Case 2 compared to Case 1. This demonstrates the effectiveness of our proposed method of using EV charging stations to address the tight power balance problem.

TABLE 2. Comparison of tight power balance disposal results.

Case	Operation cost (\$)	Wind spillage (MWh)	Load shedding (MWh)	Thermal unit ramp (MWh)	Saving of thermal units' ramp (MWh)
Case 1	672428.59	80.66	851.79	7072.81	0
Case 2	593619.73	66.24	345.69	4692.31	2908.07

B. THE IMPACT OF THE SCALE OF EV

In order to show the applicability of our proposed method, 10 scenarios of the EV scale are set with the scale of 20%, 40%, 60%, 80%, 100%, 120%, 140%, 160%, 180% and 200% of the original EV scale. The impact of EV scale on the system operation cost and saving of thermal units' ramp shown in FIGURE 2 while the impact of EV scale on load shedding is shown in FIGURE 3.

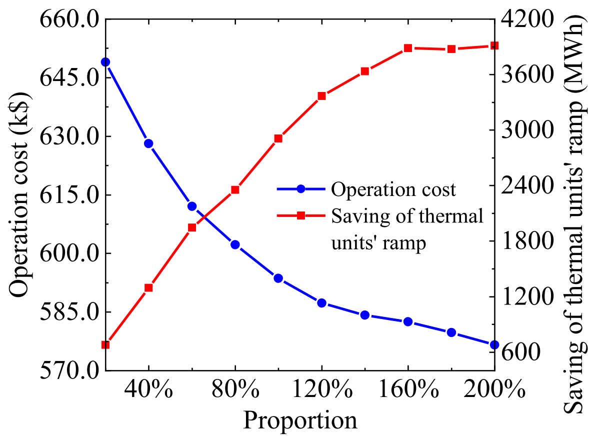

FIGURE 2. Impact of EV scale on the system operation cost and saving of thermal units' ramp.

It can be seen from FIGURE 2-3 that, with the increasing scale of EV, the system operation cost and load shedding continue to decrease, while the saving of thermal units' ramp increase. This indicates the increase in EV scale improves the tight power balance disposal level, which validates the applicability of the proposed method.

C. THE IMPACT OF DIFFERENT WIND POWER PENETRATION RATES

In order to show the applicability of our proposed method, the following three scenarios of wind power output are shown in FIGURE 4.

TABLE 3. Comparison of tight power balance disposal results of scenarios with different wind power penetration.

Scenario	Case	Operation cost ($)	Wind spillage (MWh)	Load shedding (MWh)	Thermal unit ramp (MWh)	Saving of thermal units' ramp (MWh)
Scenario 1	Case 1	777211.76	0.41	1325.51	7272.41	0
	Case 2	675596.46	0	641.58	4920.22	3055.65
Scenario 2	Case 1	672428.59	80.66	851.79	7072.81	0
	Case 2	593619.73	66.24	345.69	4692.31	2908.07
Scenario 3	Case 1	602242.36	83.28	938.53	5896.49	0
	Case 2	524393.85	0	385.85	4889.34	1713.66

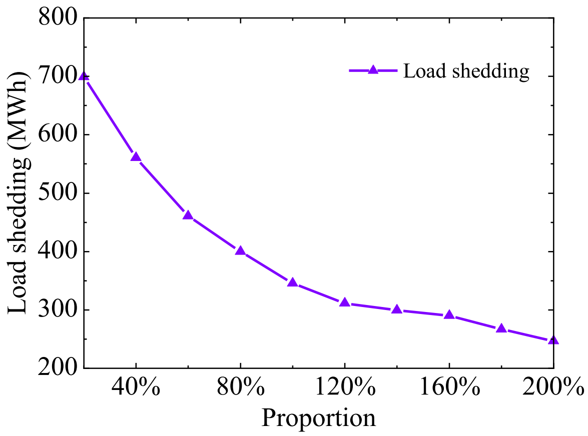

FIGURE 3. Impact of EV scale on load shedding.

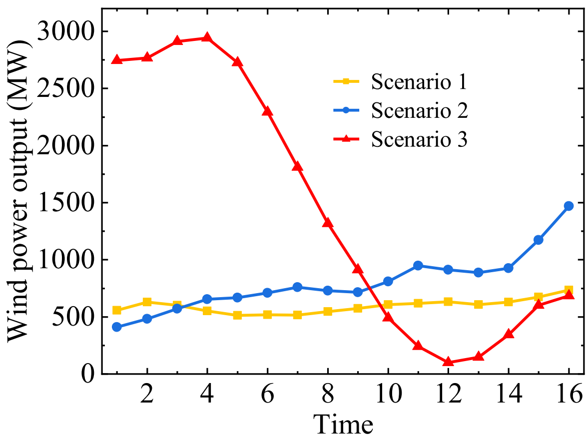

FIGURE 4. Wind power output for different scenarios.

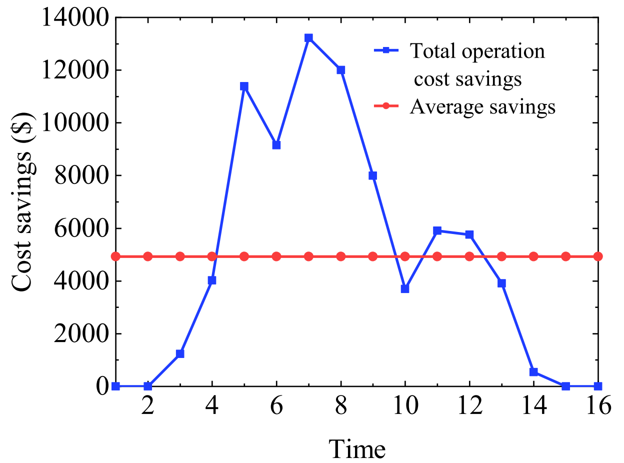

FIGURE 5. Total operation cost savings and the average savings with case 2 relative to case 1.

Scenario 1: wind power penetration rate is 9.68%, with low wind power output volatility; scenario 2: wind power penetration rate is 19.35%, with high wind power output volatility; scenario 3: wind power penetration rate is 38.70%, with the highest wind power output volatility.

Under the above three different wind power penetration scenarios, the operation cost, wind spillage, load shedding, thermal unit ramp and saving of thermal units' ramp of the tight power balance disposal are shown in TABLE 3.

As shown in TABLE 3, without the integration of EV charging stations, the operation cost and thermal unit ramp of scenario 1 are the highest; the operation cost and thermal unit ramp of scenario 2 are in the middle level; the operation cost and thermal unit ramp of scenario 3 are the lowest. After the integration of EV charging stations, the operation cost, wind spillage, load shedding and thermal unit ramp of each scenario are all reduced to a certain degree.

Under the three different wind power penetration scenarios, EV charging stations are able to increase system flexibility and improve security and economic operation of the system. The proposed method can accommodate different wind power penetration scenarios, which verifies the applicability of the tight power balance disposal strategy.

D. RESULTS ANALYSIS

FIGURE 5 shows the total operation cost savings and the average savings with case 2 relative to case 1. We evaluate the results by comparing the total operation cost savings and the average savings with Case 2 relative to Case 1 for each time period.

As shown in FIGURE 5, in time periods 1-4, 10 and 13-16, the total operation cost savings are lower than the average. Especially, the total operation cost saving is zero in the time periods 1-2 and 15-16. This is due to the uncertainty of EVs, there are no EVs in charging stations in these periods. From Section V.B., it is clear that the regulation capacity of EV charging stations is related to the EV scale. In the above time periods, the relatively small EV scale leads to the insufficient regulation capacity.

VI. CONCLUSION

In this paper, to address the tight power balance problem in power systems with high wind power penetration, a tight power balance disposal strategy considering the flexibility of EV charging stations is established. The following conclusions are obtained through the numerical simulation results:

The integration of EV charging stations provides flexible ramp to the system, so that the regulation capacity of thermal units will be improved to accommodate wind power and meet power load balance. Therefore, the wind spillage and load shedding due to insufficient system flexibility and installed generation capacity are reduced, and the system flexibility, security and economic operation level are improved.

The simulation results compare the impact of different scale of EV and indicate the increase in EV scale improves the tight power balance disposal level. The impact of different wind power penetration rates also shows the proposed method can accommodate different wind power penetration scenarios.

However, the current method still has shortcomings as follows. First, the model is solved by the commercial software CPLEX without proposing a efficient algorithm. When encountering a great number of variables and constraints, the time consumption of solving the model will increase significantly. Therefore, to improve the efficiency of solving the model, efficient algorithm should be developed to solve the model. In addition, in this paper, the resources to provide flexibility for the system only involve EV charging stations, yet many other flexible resources such as energy storage, responsive loads, etc., also have great potential. For further study, our next step can apply energy storage and responsive loads in the proposed method to both release their potential and further promote the flexibility of the system.

APPENDIX

A. SETS AND INDEX

N_T, t	Set and index of time of tight power balance disposal.
N_I, i	Set and index of thermal units.
N, n	Set and index of electric vehicles (EVs).
N_{PL}, pl	Set and index of electric vehicle charging stations.
N_W, w	Set and index of wind power units.
N_J, j	Set and index of loads.
N_L, l	Set and index of transmission lines.

B. PARAMETERS

$N_{pl,t}^{PL,Sc}$	Aggregated number of EVs in charging station.
$SOE_{pl,t}^{PL,Sc}$	Aggregated state of energy (SOE) of charging station due to arrival/departure of EVs (MW).
$Cap_{pl,t}^{PL,Sc}$	Aggregated capacity of charging station due to the arrival/departure of EVs (MW).
$\gamma^{disch\arg e/ch\arg e}$	Discharging/charging rates of EVs (kW/h).
$\eta_{Ch}^{PL}, \eta_{Dch}^{PL}$	Charging and discharging efficiency of charging stations (%).
$\psi_{pl,t}$	Net electrical discharging percentage due to contract of EV owners for desired SOC (%).
$SOC_{pl}^{PL,\max/\min}$	Maximum and minimum range of SOC of charging station *pl* (%).
$\lambda_{i,t}^{G\_sp/ns}$	Offered cost of spinning and non-spinning reserve of thermal unit *i* at time *t* ($/MWh).
$\lambda_{i,t}^{G\_reg/rep}$	Offered cost of regulation and replacement reserve of thermal unit *i* at time *t* ($/MWh).
$\lambda_{i,t}^{G\_up/dn}$	Offered cost of up and down flexible ramping capacity of thermal unit *i* at time *t* ($/MWh).
$\lambda_{pl,t}^{PL\_Eng}$	Offered cost of discharging of charging station *pl* at time *t* ($/MWh).
$\lambda_{pl,t}^{PL\_sp/ns}$	Offered cost of spinning and non-spinning reserve of charging station *pl* at time *t* ($/MWh).
$\lambda_{pl,t}^{PL\_reg/rep}$	Offered cost of regulation and replacement reserve of charging station *pl* at time *t* ($/MWh).
$\lambda_{pl,t}^{PL\_up/dn}$	Offered cost of up and down flexible ramping capacity of charging station *pl* at time *t* ($/MWh).
$\lambda_{w,t}^{WT\_spill}, \lambda_{j,t}^{LS}$	Cost of wind spillage and load shedding ($/MWh).
$R_i^{up/dn}$	Maximum ramp up/down capability of thermal unit *i* (MW/min).
τ	Time resolution in minutes (min).
$p_i^{\max/\min}$	Maximum/minimum active power of thermal unit *i* (MW).
$p_{w,t}^{WT\max}$	Maximum active power of wind power unit *w* at time *t* (MW).
P_t^{NL}	Net load at time *t* (MW).
$P_t^{NL\max/\min}$	Upper and lower limits of net load fluctuation at time *t* (MW).
κ	Net load fluctuation coefficient (%).
$FRUN_t$	Up flexible ramping demand at time *t* (MW).
$FRDN_t$	Down flexible ramping demand at time *t* (MW).
$D_{j,t}$	Load *j* at time *t* (MW).
$P_l^{L\max}$	Transmission flow limit of line *l* (MW).
G_{l-i}	Generation shift distribution factor of thermal unit *i* to line *l*.
G_{l-w}	Generation shift distribution factor of wind power unit *w* to line *l*.

G_{l-pl} Generation shift distribution factor of charging station pl to line l.

G_{l-j} Generation shift distribution factor of load j to line l.

C. VARIABLES

$p_{pl,t}^{En,PL2G}$ Power from charging station pl to the grid at time t (MW).

$p_{pl,t}^{En,G2PL}$ Power from the grid to charging station pl at time t (MW).

$FRU_{pl,t}^{PL}$ Up flexible ramping capacity of charging station pl at time t (MW).

$FRD_{pl,t}^{PL}$ Down flexible ramping capacity of charging station pl at time t (MW).

$SP_{pl,t}^{PL}/NS_{pl,t}^{PL}$ Spinning/non-spinning reserves of charging station pl at time t (MW).

$REG_{pl,t}^{PL\_up/dn}$ Up/down regulation reserves of charging station pl at time t (MW).

$REP_{pl,t}^{PL}$ Replacement reserves of charging station pl at time t (MW).

$u_{es,t}^{PL2G}$, $u_{es,t}^{G2PL}$ 0-1 variables denoting that charging station pl is in the state of energy from charging station to grid or from grid to charging station at time t.

$SOE_{pl,t}^{PL}$ SOE of charging station pl at time t (MW).

$p_{i,t}$ Active power of thermal unit i at time t (MW).

$MPC_{i,t}(\cdot)$ Operation costs of thermal unit i at time t (MW).

$FRU_{i,t}^{G}/FRD_{i,t}^{G}$ Up and down flexible ramping capacity of thermal unit i at time t (MW).

$SP_{i,t}^{G}/NS_{i,t}^{G}$ Spinning and non-spinning reserves of thermal unit i at time t (MW).

$REG_{i,t}^{G\_up/dn}$ Up and down regulation reserves of thermal unit i at time t (MW).

$REP_{i,t}^{G}$ Replacement reserves of thermal unit i at time t (MW).

$LS_{j,t}$ Load shedding of load j at time t (MW).

$p_{w,t}^{WT}$ Active power of wind power unit w at time t (MW).

$P_{w,t}^{WTspill}$ Wind spillage of wind power unit w at time t (MW).

$FRU_{w,t}^{WT}$ Up flexible ramping capacity of wind power unit w at time t (MW).

$FRD_{w,t}^{WT}$ Down flexible ramping capacity of wind power unit w at time t (MW).

FRU_{t}^{LS} Up flexible ramp provided by load shedding at time t (MW).

$FRD_{t}^{WTspill}$ Down flexible ramp provided by wind spillage at time t (MW).

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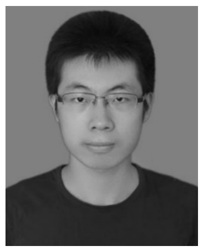

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