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Dynamic frequency response from electric vehicles in the Great Britain power system

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Abstract With the large penetration of renewable energy, fulfilling the balance between electricity demand and supply is a challenge to the modern power system. According to the UK government, the wind power penetration will reach 30% by the year 2020. The role of electric vehicles (EVs) contributing to frequency response was investigated. A dynamic frequency control strategy which considers the comfort level of vehicle owners was developed for EVs to regulate their power consumption according to the deviation of system frequency. A simulation model of a population of EVs equipped with such control was implemented in Matlab/Simulink platform. In this paper, a simplified Great Britain power system model is used to study the contribution of EVs to dynamic frequency control. The case study showed that using EVs as a demand response resource can greatly reduce the frequency deviations. And the rapid response from EVs can help reduce the operation cost of conventional generators.

Keywords Electric vehicles (EVs), Dynamic frequency response, Vehicle to grid (V2G), State of charge (SOC)

1 Introduction

With the increasing concerns over the environmental and energy problems, the concept ‘low-carbon economy’ has been more and more popular. Consequently, several countries around the world have taken appropriate means in order to de-carbonize the power system and transport sector. In the UK, a large scale of renewable energy will come from wind turbines in the following years. It is estimated that the wind generation capacity will reach 30 GW within a generation capacity of 100 GW which serves a load of around 60 GW by the year of 2020. To realize the target of decarbonizing the domestic transport sector, the number of EVs will be greatly increased, which will play an important role in the future [1].

However, a large scale integration of wind generation may bring inevitable concerns over the power system operation due to the variability of wind generation, especially the active power balance between the generation and demand. As a consequence, a high penetration of wind energy will definitely increase the difficulty in frequency control. In order to keep the system frequency within an acceptable range, several researches focused on the frequency stability of power system in the presence of high renewable energy penetration. Oudalov and Pascal used battery energy storage system (BESS) for frequency control [2, 3]. BESS can substantially reduce the frequency deviations caused by sudden supply/demand variations. However the cost of BESS is very high and it is difficult to bring profit by now. The impact of wind turbine on the system frequency stability in the UK was investigated by Pearmine [4]. Ramtharan studied the capability of doubly fed induction generator wind turbines to serve the frequency control [5]. A frequency droop controller was developed to realize that function by adjusting the generator torque set point. Short investigated the possibility of utilizing refrigerators as frequency response resource [6].

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The temperature set points which adjust according to the system frequency were used to decide the on-off state.

Recently, EV technology is one of the distributed energy technologies that have been increasingly deployed. The vehicle-to-grid (V2G) concept allows EV to serve as a mobile battery storage unit. With a bidirectional power interface, EV battery could either charge or discharge. The capability of storing energy and the instantaneous active power control of fast-switching converters of EVs are two attractive features that enable EVs to provide various ancillary services, e.g., the provision of primary frequency control in island and grid connected systems [7–9]. A droop control allows EVs to adjust their charging power in response to the system frequency signal. The controlling effect of EVs for frequency control was investigated in [10], which controlled the system frequency by a sudden disconnection of all EVs from the power system following a large disturbance in the system. However, this control approach can result in undesired condition over frequency responses when the response power of EVs is more than the power imbalance in the system. Also, the effect of EVs constraints on the provision of dynamic frequency response in the Great Britain (GB) power system has not been discussed comprehensively yet.

In this paper, the effect of utilizing EVs for dynamic frequency response in the GB power system at the year of 2020 was studied. A dynamic frequency control (DFC) strategy which considers the comfort level of EV owners was developed for EVs to regulate their power consumption dynamically according to the deviation of system frequency along a typical day. A participation factor k with battery state of charge (SOC) was introduced to evaluate the comfort levels of EV owners. Based on a simplified GB power system model, the effect of EVs in dynamic frequency response was studied considering the V2G characteristic. Results of two EV charging scenarios: "dumb" charging, and "smart" charging, were compared.

2 Frequency control in the GB system

2.1 Frequency control

To maintain the frequency stability, the upper/lower frequency limit of the GB power system is 49.5/50.5 Hz [11]. In the UK, the power system is designed to accept a loss of 1320 MW generation. On this occasion, the frequency deviation will be less than 0.8 Hz and the frequency will be restored to 49.5 Hz within 60 seconds. Figure 1 shows a typical frequency transient for a generation loss of 1320 MW based on a severe frequency event [12, 13]. To reach the target of 'low-carbon economy', more wind energy will be integrated into the power system through power electronic interfaces. Considering the uncertainties brought by wind power, the GB power system needs to be able to accept up to a new maximum of 1800 MW generation [14]. Therefore larger frequency response capacity is likely to be required.

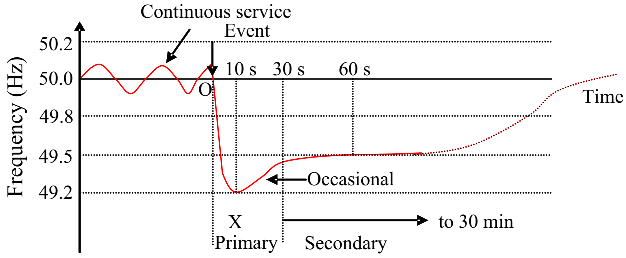


Fig. 1 Frequency curve with a loss of 1320 MW generation

2.2 Simplified GB power system model

In this paper, a simplified system model was utilized to represent the GB system, as shown in Fig. 2. This model considers the characteristics of generators and frequency dependent loads. The power plants were represented in the model by blocks which consist of governors and turbines. The power plants adjust their power output according to the frequency deviation. Relevant parameters are shown in Table 1 [15, 20]. R_{eq} represents the speed control of turbines and operates on the speed deviation which is formed between the actual speed and the reference speed. T_{G} is a typical time constant related to the governor actuator. A transient droop compensation was set between the governor and the turbine. T_1 and T_2 are time constants of lead-lag transfer function. The turbine model is characterized by a time constant T_{T}. It represents the mechanical power output following the governor action. H_{eq} is set in consideration of the operational generation capacity in the 2020 system. D is a single damping constant which represents the damping of frequency dependent loads. T_{EV} is the time constant which represents EV charger time delay. These parameters capture the characteristics of different governors and turbines. The values were set according to a

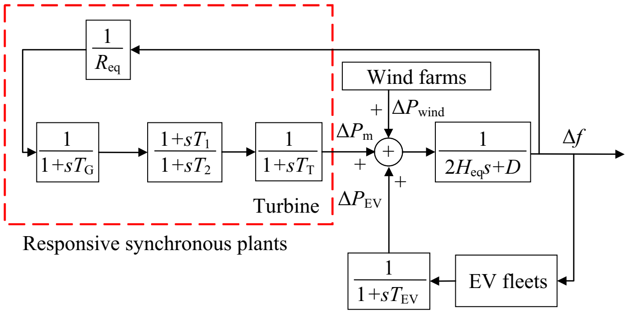


Fig. 2 Simplified GB power system model

Table 1 Parameters of the simplified GB system

Parameters	Value
R_{eq} (p.u.)	−0.09
T_G (sec)	0.2
T_1 (sec)	2
T_2 (sec)	12
T_T (sec)	0.3
H_{eq} (sec)	4.44
D (p.u.)	1

serious frequency event happened in the GB power system in 2008 [13].

Most of the responsive synchronous plants in service at present will remain in service by 2020. New plants to be built will share similar characteristics. Thus the characteristics of responsive synchronous plants will be changeless by 2020. Only the operational capacity of plants will vary because some of them will be replaced by wind plants.

Because of the intermittency of wind energy, wind farms will play a significant role in the system. The power disturbance from the wind farms is represented by ΔP_{wind}.

3 Dynamic frequency control strategy

3.1 A generic EV charging model

A generic EV charging model (GECM) is used to simulate the charging and discharging procedure of EV batteries. As depicted in Fig. 3, the nonlinear GECM is composed of a generic EV charger model and a generic battery model.

3.1.1 A generic EV charger model

The model is composed of a converter and an inverter. The voltage is adjusted to an appropriate level by the converter for EV battery. The reactor L connects the inverter and the power system. The resistance of the reactor is represented by R_C. The inverter operation is based on a pulse-width modulation (PWM) switching technique. The active/reactive power controls were employed through vector control and were used to generate modulating signals for PWM [16]. The current i is calculated as follow [17, 18]:

$$L\frac{di}{dt} + R_c i - V_{\text{grid}} + V_{\text{EV}} = 0 \tag{1}$$

The voltage of EV battery (V_{EV}) is calculated by [17, 18]

$$V_{\text{EV}} = \alpha M V_{\text{DC}} \sin(\omega t + \delta) \tag{2}$$

where M is the PWM modulation index used for inverter; δ is the angle between V_{EV} and V_{grid}; $\alpha$is a constant (0.5 or 1) which depends on the exact topology of the inverter.

Equation (1) indicates that the current (or power) exchanged between the battery and the system is governed by a first order differential equation. Thus a first order lag with a time constant $T_{\text{EV}} = L/R_c$ was used for frequency studies.

3.1.2 A generic battery model

As shown in Fig. 4, the generic battery model is composed of a voltage source and a constant resistance. The model that only uses battery SOC as a state variable is chosen to accurately reproduce the manufacturer's curves for four major types of battery chemistries.

The battery voltage V_{batt} is described by

$$V_{\text{batt}} = E - R_b i \tag{3}$$

$$E = E_0 - \frac{K}{SOC} + A\exp\left(-B\int_0^t i\mathrm{d}t\right) \tag{4}$$

$$SOC = 1 - \frac{\int_0^t i(t)\mathrm{d}t}{Q} \tag{5}$$

where E_0 is the battery constant voltage; K is the polarisation voltage; Q is the battery capacity; i is the charging current; A is the exponential zone amplitude; B is

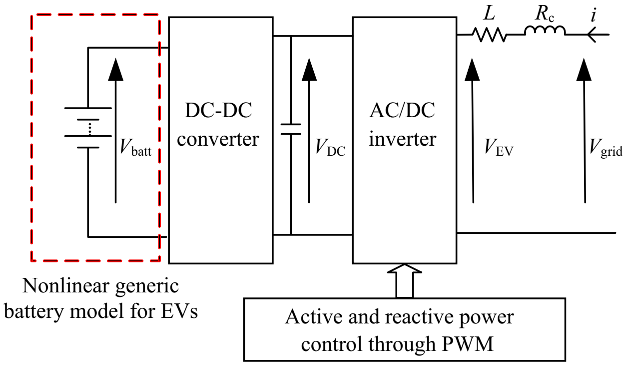


Fig. 3 A generic EV charger model of EV

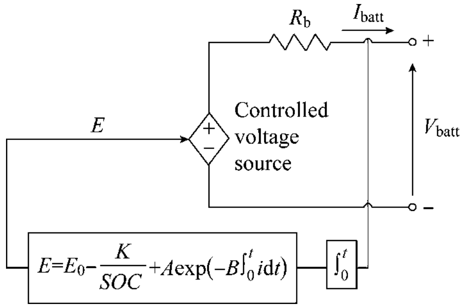


Fig. 4 A generic battery model for EVs

the exponential zone time constant inverse; R_b is the internal resistance.

To simplify the integral part, the charging power P is calculated as

$$P = E_0 i - \frac{Ki}{SOC} + Ai\exp(-Bit) - R_b i^2 \tag{6}$$

where i is a constant charging current.

There are only a few parameters in this proposed generic battery model. Based on the battery type and capacity, the SOC can be calculated using this model.

3.2 Dynamic frequency control strategy

A dynamic frequency control strategy which considers the comfort level of the EV owners is developed for the EVs to regulate their power consumption dynamically according to the system frequency deviation. In this strategy, the comfort level is evaluated by the participation factor k. Instead of tripping EVs directly, the SOC set point is varied dynamically according to the deviations of frequency and k. EVs can serve the frequency regulation in two ways. One approach would be to switch off (on) EVs that are being charged (idle). The other approach is supporting the grid through discharging. There are two control modes in the developed dynamic frequency control strategy.

(1) *V1G mode*

In V1G mode, EVs participate in frequency response through adjusting their power consumption. The SOC set point of EVs is controlled as

$$\begin{aligned} & SOC_{\max}^{\text{V1G}} = SOC_{\max}^{\text{normal}} + k\Delta f \\ & \Delta f = f - f_0 \\ & SOC_{\min} \le SOC_{\max}^{\text{V1G}} \le 1 \\ & \Delta f \ge \Delta f_{\text{cr}} \end{aligned} \tag{7}$$

where $SOC_{\max}^{\text{normal}}$ is nominal high SOC set point of EV battery; $SOC_{\max}^{\text{V1G}}$ is the modified high SOC set point under V1G mode; $SOC_{\min}$ is the minimum SOC value for satisfying the travelling requirement of EV owners; f_0 is the system nominal frequency e.g. 50 Hz for the GB system; f is the actual system frequency; Δf_{cr} is the value of frequency decrease when $SOC_{\max}^{\text{V1G}} = SOC_{\min}$; k ($k > 0$) is the participation factor of EVs. The larger value of k, the larger variation of $SOC_{\max}^{\text{V1G}}$. As a result, the frequency response capability is larger, and the travelling comfort level is lower, and vice versa.

When system frequency increases ($\Delta f > 0$), the EVs with SOC between $SOC_{\max}^{\text{normal}}$ and $SOC_{\max}^{\text{V1G}}$ were changed from idle status to charging status to increase their power consumption.

When system frequency decreases ($\Delta f_{\text{cr}} < \Delta f < 0$), the EVs with SOC between $SOC_{\max}^{\text{normal}}$ and $SOC_{\max}^{\text{V1G}}$ were changed from charging status to idle status to decrease their power consumption. When $\Delta f = \Delta f_{\text{cr}}$, the EV resources for V1G mode is used up. The EVs turn to V2G mode which starts from $SOC_{\max}^{\text{V2G}} = 1$.

(2) *V2G mode*

When the system frequency falls lower than Δf_{cr} ($\Delta f < \Delta f_{\text{cr}} < 0$), the V2G mode is used for frequency control. In V2G mode, EVs participate in frequency response through adjusting their discharging power. The EVs with SOC between 1 and $SOC_{\max}^{\text{V2G}}$ discharge their stored battery energy back to the system. The SOC set point of EVs is controlled according to

$$\begin{aligned} & SOC_{\max}^{\text{V2G}} = 1 + k\Delta f + (SOC_{\max}^{\text{normal}} - SOC_{\min}) \\ & SOC_{\min} \le SOC_{\max}^{\text{V2G}} \le 1 \\ & \Delta f \le \Delta f_{\text{cr}} \end{aligned} \tag{8}$$

where $SOC_{\max}^{\text{V2G}}$ is the modified high SOC set point under V2G mode.

Figure 5 is used to illustrate the dynamic frequency control strategy. EVs connecting to system are divided into charging group, discharging group and idle group.

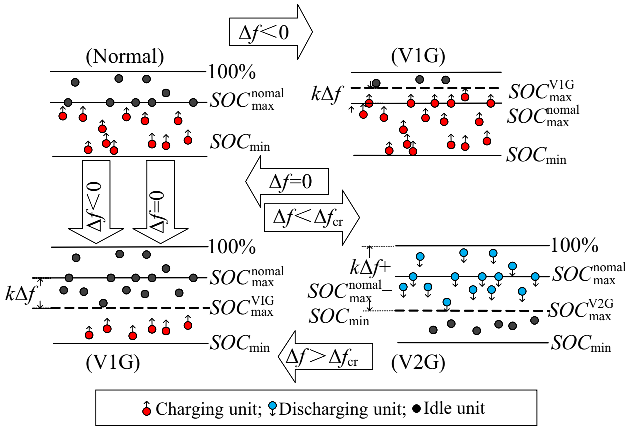


Fig. 5 Dynamic frequency control strategy

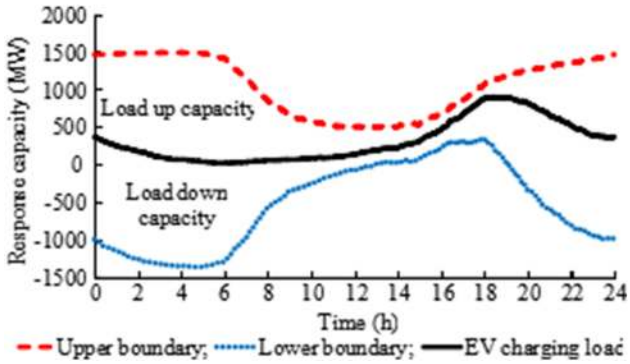


Fig. 6 Response capacity (dumb charging)

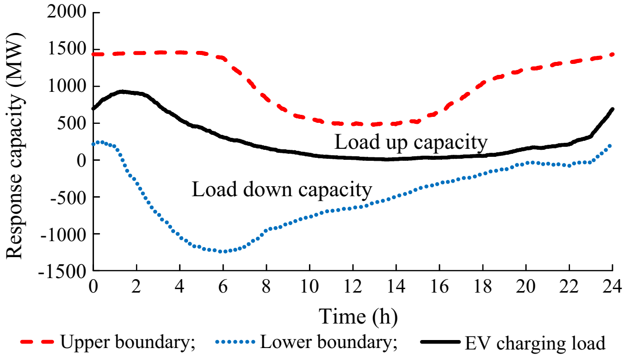


Fig. 7 Response capacity (smart charging)

The two control modes switch smoothly following the frequency deviation, which can serve the frequency regulation of power system. At the same time, the comfort level is considered in the strategy.

4 Case study

The GB power system model discussed above was utilized to study EVs' ability to serve frequency response. Two charging scenarios proposed in [19] (dumb charging & smart charging) were used in this section to consider the travel behaviors and comforts of EV owners. The number

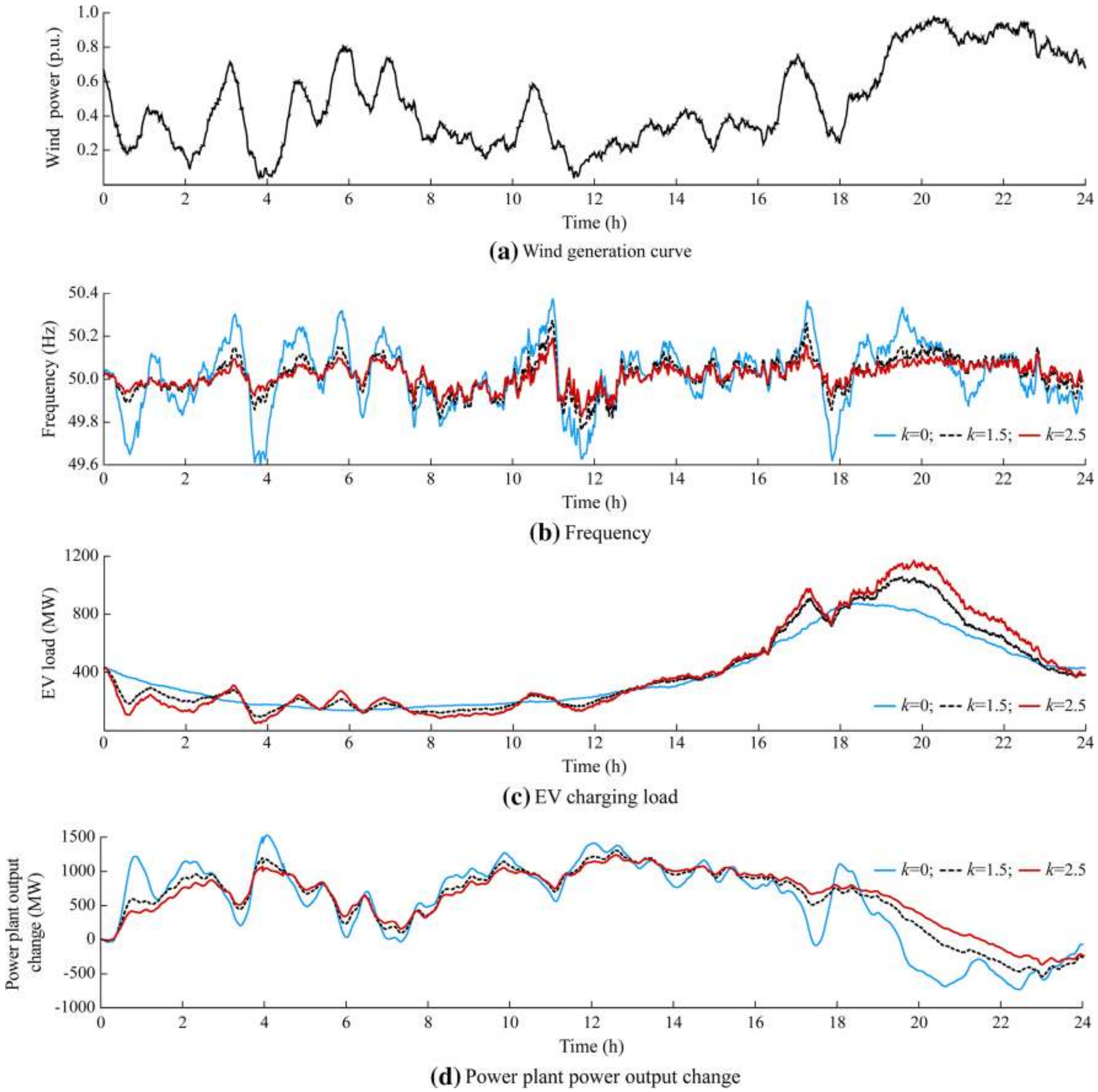


Fig. 8 Simulation results (dumb charging)

of EVs which are anticipated in 2020 is the same as [20]. They constitute 1.74% of vehicles in GB in the year of 2011 [21]. The charger parameter L is set as 7 mH and R_c as 0.2 Ω for the EV charging model ($T_{EV} = 35$ ms) [20]. The SOC lower limit $SoC_{\min}$ is 30%. The normal SOC upper limit $SOC_{\max}^{\text{normal}}$ is 80%.

4.1 Response capacity of EVs

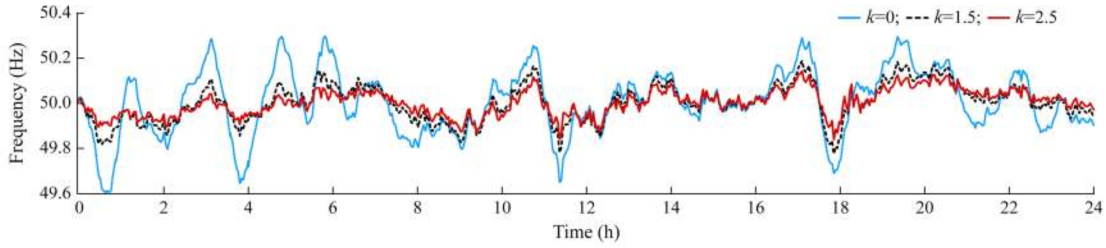
In this section, the EV aggregation model is built to investigate the capacity during a whole day considering EV characteristics and travel behaviors. It is built with the consideration of battery type, battery capacity, energy consumption per kilometer, daily travel distance, daily travelling time and demand SOC levels for travelling [22]. In dumb charging, all of the EVs are considered to start charging soon after their daily trip. Smart charging is used to shift the charging load from peak load time to valley hours.

Figures 6 and 7 show the EV charging power with its upper/lower boundary, which show the available response capacity (load up/ load down) of EVs along a whole day. The upper boundary refers to the charging power of EVs that with SOC lower than 100% all turn to charging status. The lower boundary refers to the charging power of EVs that with SOC higher than 30% all turn to discharging status. Due to the transportation behaviors of EVs, the available response capacity changes over time. The response capacity is relatively small during the day time (from 6:00 to 18:00) [25].

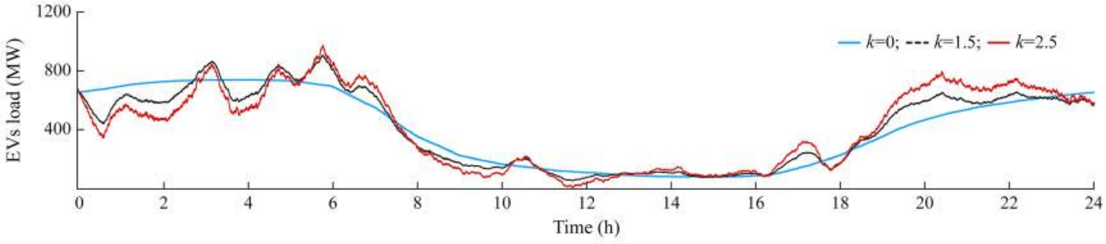
In dumb charging, as shown in Fig. 6, larger response capacity is obtained at night (from 18:00 to 6:00). Smart charging fails to charge immediately after EVs come back from daily trips. Thus the load down capacity is smaller from 18:00 to 2:00, as shown in Fig. 7. The capacity has a strong impact on the effect of frequency response.

4.2 Simulation results for frequency response

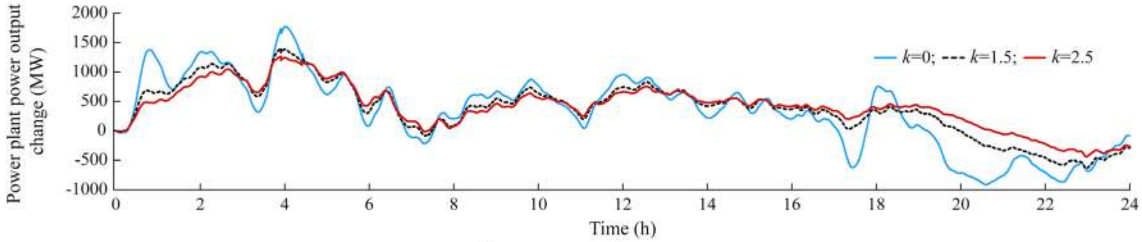
The simulation results under dumb charging are shown in Fig. 8. Fig. 8a shows the wind generation curve (P_{wind}) along a day. The intermittence of wind power will increase the difficulty in frequency control. As depicted in Fig. 8b, the frequency fluctuations with EVs' response ($k > 0$) are



(a) Frequency



(b) EV Charging load



(c) Power plant power output change

Fig. 9 Simulation results (smart charging)

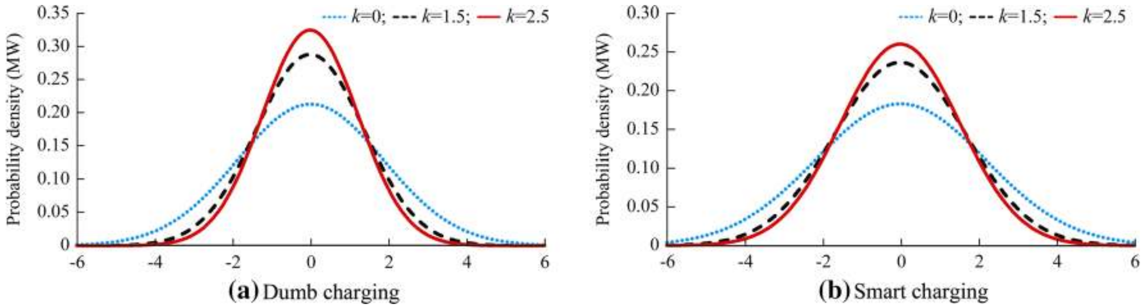


Fig. 10 Probability density of power plant output variation on minute-scale

much smaller than that without EVs' response ($k = 0$). A larger k means a better frequency control effect. When $k = 0$, the frequency deviation is within [−0.4, 0.4 Hz]. With the increasing value of k, the participation factor of EVs increases. The frequency deviation is mainly within [−0.2, 0.2 Hz] when k equals to 1.5 and 2.5. The effect of frequency response is also constrained by the available response capacity of EVs, which can be seen in Fig. 8b. In the day time (6:00–18:00), the frequency deviation is mainly within [−0.2, 0.2 Hz]. The range is narrowed to [−0.1, 0.1 Hz] at night (18:00–6:00). This can also be verified by Fig. 6.

Figure 8c shows the EV charging load along the day. The curve with $k = 0$ shows the EV charging load without participating in frequency response. EV charging load will either decrease when $\Delta f < 0$ or increase when $\Delta f > 0$. The load variation will increase with the growth of k. EV charging profiles are integrated into the 24-hour load demand [23, 24].

Figure 8d shows the power output variations from conventional power plant along a whole day. With EVs participating in frequency response, the power output fluctuation of power plant is reduced. A larger k brings smaller power fluctuation range.

The simulation results under smart charging are shown in Fig. 9. Due to the lack of 'load down' capacity at night, the frequency response from 17:30 to 18:30 is worse than that with dumb charging, as shown in Fig. 9a. Smart charging can also cause a shift of EV charging load, as shown in Fig. 9b–c. The comparison results between dumb and smart charging illustrate that the ability of EVs to provide dynamic frequency service has a close relationship with the EV charging scenarios.

The benefits from EV frequency response can also be illustrated by the probability density distribution of power plant output in Fig. 10. With the growth of k, the fluctuation of the power output variation is reduced with both dumb and smart charging scenarios, which can significantly reduce the operational cost of power plants.

5 Conclusions

In this paper, we studied the potential of EVs for dynamic frequency regulation in the UK in 2020. A dynamic frequency control strategy from EVs considering the owner comfort level was developed. The strategy was embedded to the simplified GB system with a GECM for the dynamic frequency response study. The charging load under two charging scenarios (dumb charging & smart charging) with two control modes were considered. The following conclusions can be drawn:

1) The EV aggregation have great potential for providing system dynamic frequency response. Using EVs to maintain the frequency stability can significantly reduce the frequency deviations along the whole day. At the same time, the power fluctuations of conventional generators are decreased to some extent. However, the regulation capacity of EVs has a distribution along 24 hours. Thus the frequency response from traditional power plants should be scheduled dynamically along the whole day.

2) The regulation capacity of the EV aggregation to serve dynamic frequency regulation is closely related to the charging scenarios. For the EVs with dumb charging, large regulation capacity can only be reached at peak load hour of the charging loads. In contrast, smart charging is able to distribute the regulation capability to most of the time along the whole day.

3) The impact of the time delay caused by the chargers is deemed negligible as shown in the simulation results. EVs' ability to provide frequency response is closely related to the response capacity and participation factor k. Two charging scenarios (dumb/smart charging) with different available response capacity show different frequency response characteristics. In this paper, the whole EV aggregation shares the same k during the whole day. How to determine the optimum k under different conditions considering personalized demand and travelling comfort requirements of different EV owners should be studied in future research.

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