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Active power regulation for large-scale wind farms through an efficient power plant model of electric vehicles

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HIGHLIGHTS

- Considering the travelling behaviors, an efficient power plant model of EVs (E-EPP) is developed.
- The available capacity of the EV aggregation is obtained with the E-EPP model under three charging scenarios.
- A new active power regulation strategy through E-EPP is proposed for the power system with large-scale wind farms.
- With the regulation strategy, the E-EPP can effectively decrease the output variation of traditional generators.

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ABSTRACT

Considering the travelling behaviours of electric vehicles (EVs), an efficient power plant model of EVs (E-EPP) is developed for the active power regulation of the power system with large-scale wind farms. Based on the EV data base provided by the EU MERGE project, a generic V2G model (GVGM) is established. The Monte Carlo Simulation (MCS) method is implemented within the E-EPP to obtain the available response capacity of the EVs. A new active power regulation strategy based on the E-EPP is developed. A modified IEEE 118-bus system integrated with large-scale wind farms is used to verify the E-EPP model with the active power regulation strategy under different charging scenarios (dumb charging, smart charging and hybrid charging). The simulation results show that the E-EPP can improve the operating security and stability of the power system. The operation cost and the carbon emission are decreased by introducing large-scale wind farms.

1. Introduction

In recent years, the wind energy has drawn more and more attention around the world for its energy-saving and low-carbon features [1]. A number of countries have taken specific initiatives to de-carbonise their power systems by encouraging wind power [2–4]. In the UK, it is anticipated that a large proportion of renewable energy in the future will come from wind turbines. There may be up to 30 GW of wind generation within a total generating capacity of some 100 GW serving a load of 60 GW by 2020 [5].

The uncertainty of wind power introduces inevitable concerns over the stable operation of a power system. A high penetration of wind power will increase the difficulty in balancing power generation and demand. Without effective active power regulation, more spinning reserve is required to increase the operating stability of the power system [6]. The lack of spinning reserve will significantly limit the utilisation level of wind energy. Relevant studies have been carried out in this field. The impact of wind power on the thermal power plants was investigated in [7–10]. It is indicated that the operation cost and the carbon emission of the thermal power plants used for wind power mitigation are increased. With an increasing penetration of wind energy, the spinning reserve is further required for the wind-thermal power system [11]. The Energy Storage System, such as batteries and flywheels, are used to mitigate the output variation of wind power [12,13]. However, the cost of an energy storage system is usually still high for a large scale deployment by now.

In recent years, there have been growing interests in the flexibility at the demand side. The demand response resources are able to serve as an additional option for the spinning reserve of a power system [14–16]. The imbalance power caused by the wind power was offset by controlling the interruptible loads such as heat pumps in [17,18].

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Electric vehicles (EVs) have been proved to be an effective resource for demand response, which has gained increasing interests by researchers in recent years. With the vehicle-to-grid (V2G) technology, an EV can act as a mobile battery energy storage system, which can realise a bi-directional power flow with the power system [19]. According to the UK Department for Business Innovation and Skills, the number of EVs in the UK will be greatly increased, which has been estimated at 550,000 in 2020 [20]. A large number of EVs are able to provide a considerable reserve capacity and various types of ancillary services for the power system. Due to the flexibility of charging time, the EVs can serve as a load shaping-tool to alleviate the system peak load [21,22]. Meanwhile, the EVs are able to provide frequency regulation service to the power system relying on their rapid responding ability [23,24]. Through adjusting their charging power, the EVs are able to balance the power supply and the power demand, which further promotes the wind power integration [25,26]. The available capacity of the EVs for reacting to the output variation of wind farms was investigated in [27,28].

The existing literature has made a good contribution for EVs to participating in load profile shaping, frequency regulation and power balancing, etc. of power system. However, the response capability from EVs is affected by the travelling behaviours of EV users, which leads to an obvious temporal distribution along a day. This characteristic should be further considered for EVs when participating in the operation of power system.

In this paper, an efficient power plant model considering the temporal travelling behaviours of EVs (E-EPP) is introduced. With the E-EPP, the EV aggregation can serve as a virtual power plant with maximum and minimum generating outputs to support the operation of the power system, which is defined as the available capacity form E-EPP. Then a new active power regulation strategy using the available capacity is proposed for the power balancing of the power system with large-scale wind farms. The imbalance power caused by the stochastic wind power is first offset by the E-EPP, while the traditional power plants are used as the backup. The active power regulation strategy is able to decease the output variation and the required capacity of spinning reserves. Meanwhile, the operation cost and the carbon emission are decreased by replacing the thermal power plants with the wind farms.

2. Framework of the active power regulation through E-EPP

2.1. The E-EPP model

The framework of the E-EPP model is shown in Fig. 1. The E-EPP is developed as an aggregator managing a large number of geographically dispersed EVs connected to the power system.

By analysing the V2G supported by the EV charger and various EV batteries, a generic V2G model (GVGM) is established which includes a generic EV charger model (GECM) and a generic EV battery model (GEBM). According to the EU MERGE Project, the EV database provides the information of EV characteristics, including battery characteristics and travelling characteristics [29]. The GVGM and the EV database are used by the Monte Carlo Simulation (MCS) to obtain the EV charging load and the available capacity during a whole day.

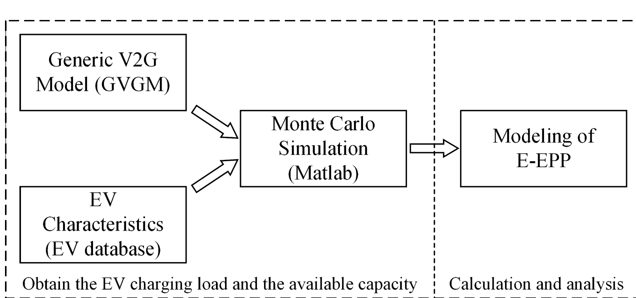

Fig. 1. The framework of the E-EPP model.

2.2. The active power regulation strategy through E-EPP

Once the E-EPP is able to be scheduled as a virtual power plant, it can provide power regulation service by replacing the traditional AGC generators. The framework of the active power regulation strategy through E-EPP is shown in Fig. 2, which is decomposed into three layers: the generation layer, the transmission layer and the E-EPP layer.

The generation layer includes the wind power and the traditional power plants. The E-EPP layer acquires the EVs' response status and the available capacity from E-EPP. The generation data and the E-EPP data from the above two layers are provided to the transmission layer. Then the transmission layer acquires the power flow data and implement the active power regulation strategy based on power flow tracing. The E-EPP layer follows the instructions from the transmission layer for power regulation through E-EPP. In the active power regulation strategy, the E-EPP is first used to offset the power variation caused by the stochastic wind power. The traditional power plants are the backup of E-EPP.

3. Formulation of the E-EPP

3.1. A generic V2G model

In this section, a GVGM is introduced to simulate the charging/discharging process of various kinds of EV batteries. The GVGM is composed of a GECM and a GEBM.

3.1.1. A generic EV charger model

As shown in Fig. 3, the GECM consists of an AC–DC rectifier and a DC–DC converter. The rectifier is connected to the power system through a reactor L_c. The heat loss of the rectifier is caused during the V2G process and the power loss is represented by the resistance R_c as suggested by [5]. The converter can step down the voltage to an acceptable level for the battery. The rectifier is controlled by a Pulse-Width Modulation (PWM) switching for V2G. The active power control is employed by the vector control, which is utilised to generate modulating signals for the PWM [30].

The current i_c between the grid and the rectifier is given by (1).

$$L\frac{di_c}{dt} + R_c i_c - V_{\text{grid}} + V_{\text{EV}} = 0 \quad (1)$$

The voltage V_{EV} is calculated by (2) [31,32].

$$V_{\text{EV}} = \alpha_v M V_{\text{DC}} \sin(\omega_v t + \delta_v) \quad (2)$$

where M is the PWM modulation index of the rectifier; δ_v is the angle between V_{grid} and V_{EV}; ω_v is the angular velocity of the power system; α_v is a constant (0.5 or 1.0) depending on the exact topology of the rectifier.

3.1.2. A generic EV battery model

As shown in Fig. 4, a simple controlled voltage source in series with a constant resistance is utilised in this GEBM [33]. The model uses the battery SOC as a state variable to reproduce the manufacturers' discharging curves of the four promising batteries (lithium-ion, lead-acid, nickel-metal-hybrid and nickel-cadmium batteries) in the future EV market.

According to the GEBM, the battery terminal voltage (V_{batt}) is described by (3) and (4):

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