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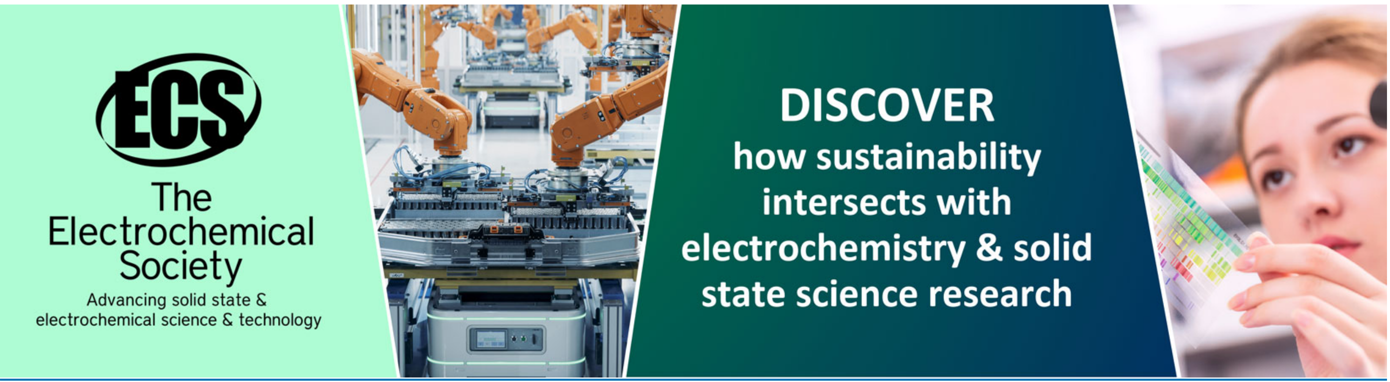

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Frequency-Voltage Characteristics Concerned Optimal Dispatch

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Abstract. The rapid development of integrated wind power bring serious challenges to power system operation. In order to address the increasing wind power curtailment problem, the frequency-voltage characteristics concerned optimal dispatch for power system with large-scale wind power integration is proposed in this paper. Through integration of the optimization of frequency characteristics and voltage characteristics into the traditional power system economic dispatch model, the flexibility resources of generation side and load sides in power systems are mobilized to promote large-scale wind power accommodation. The formulated frequency-voltage characteristics concerned optimal dispatch mathematical model is a nonlinear programming model, which is solved by the GAMS platform. The numerical analysis for an actual provincial power grid indicates that the proposed frequency-voltage characteristics concerned optimal dispatch method can promote wind power utilization efficiency and improve the economy of power system operation.

1. Introduction

Exhaustible resources are growing increasingly tense, and environmental pollution, climate changes and other issues are becoming increasingly prominent. Therefore, the clean energy revolution is imperative to force the power system to develop into an intelligent trend of the clean, environmentally-friendly and economic concept [1]. Under the new situation, a complex form of diversity, correlation and complementarity is existing in the power generation, load and grid of the power system, and the dispatching and operation of the power system are facing a serious contradiction, that is, there is great uncertainty in receiving, power transmission and grid voltage support level during the real-time balance of power generation and load power [2-3].

The goal of the dispatching and control and the power system is to realize a real-time balance of power generation and load power [4]. The key for the power system to eliminate uncertainness is how to consider control in dispatching and how to involve dispatching in control [5]. Moreover, the real-time balance of the power generation and load power may be effectively improved by making full use of the frequency and voltage regulation effects of the power system [6-8].

The power load is showing a trend of diversified development under the new situation, and the fluctuation of its demand is more and more increasing; the renewable energy generation like wind and solar energy, etc. is integrated into a power grid in the trend of rapid development, and the uncertainty in the power generation side is becoming significant. For this, the operation of the power system is facing the challenge of increasing uncertainty in the system integration. The traditional and controlled fossil energy generation is gradually replaced by the renewable energy generation. Further, the power system is facing these new problems of uncertainties elimination ability, power transmission capacity and grid voltage support level in the case of uncertain circumstances. Therefore, how to deal with mentioned-above problems is a challenge that the power system is facing under the new situation [9].

There have been many studies [10-12] on the economic dispatching of the power system in the case of uncertain situations, but it mainly focuses on matching the resource reserve with the expected uncertain deviation during the optimization process, and it is difficult to realize an effective correlation between dispatching and generation control. How to analyse the mapping relationship between the resource reserve and uncertainty? And how to deal with the balance between the power generation and the load power under uncertainty? An optimized decision integrating dispatching and control is worthy of in-depth study. The core of the active dispatching and control of the power system under uncertainty lies in a strategy of how to eliminate uncertainties in the correlation between the dispatching and control around the floatation in the frequency and voltage [13-14]. The existing studies regarding economic dispatching under uncertainty all imply that the frequency and voltage remain at rated values during dispatching, but the frequency and voltage are allowed to vary within a certain range during the actual operation of the power system. Therefore, these studies are conservative to some extent, and the dispatching is occasionally impossible in the study but is feasible in an actual situation, so wind curtailment and load shedding are inevitable. For this purpose, it is necessary to study the impact of the frequency and voltage regulation effects on the economic dispatching of the power system.

2. Mathematical model of frequency-voltage characteristics concerned optimal dispatch

The frequency-voltage characteristics concerned optimal dispatch aims at minimizing the sum of the generation cost, reserve cost, expected wind power curtailment cost while satisfying all the physical constraints of power system operation. The primary frequency response characteristics of generation units and electric loads as well as the voltage response characteristics of all loads are taken into account in the formulated model. In addition, penalty cost for frequency error and voltage error are added into the objective function to ensure the expected power quality. Through integration of the optimization of frequency characteristics and voltage characteristics into the traditional power system economic dispatch model, the flexibility resources of generation side and load sides in power systems are mobilized to promote large-scale wind power accommodation.

2.1. Objective functions

The objective function of the model is to minimize the sum of generation cost, reserve cost, wind power curtailment cost and the corresponding penalty of frequency-voltage error, which is as follows:

$$\min \sum_{g\in N_G}\left\{f_g\left(P_g\right)+c_g^R\cdot\left(R_g^U+R_g^D\right)\right\}+\sum_{w\in N_W}\sum_{s\in N_S}\eta_w\Delta P_{w,s}+\left(V-V_N\right)^2\cdot\gamma_1+\left(f-f_N\right)^2\cdot\gamma_2 \tag{1}$$

where N_G indicates the set of thermal power generation units; N_W denotes the set of wind farms; η_w represents the penalty coefficient for wind farm w; N_S represents the set of random scenarios for wind farm; $P_{g,t}$ indicates the output power of Generation unit g during Period t in a predicted scenario; $f_g(\cdot)$ indicates the generation cost function of generation unit g, and quadratic function is used here; c_g^R indicates the reserve cost coefficient of generation unit g; R_g^U and R_g^D indicate the reserve capacity of generation unit g for up-regulation and down-regulation; V_N indicates the rated voltage of the load; V indicates the actual voltage of the load; γ_1 indicates a penalty coefficient when the voltage deviates from the rated value; f_N indicates a rated frequency; f indicates an actual frequency value of the system; γ_2 indicates a penalty coefficient when the frequency deviates from the rated value.

2.2. Constraints

Constraints involve the technical constraints under predicted scenarios and error scenarios.

Constraints for the scenario of the expected value.

1) Power balance constraints:

$$\sum_{g\in N_G} P_g + \sum_{w\in N_W} P_w = \sum_{d\in N_D} P_d \tag{2}$$

where P_w indicates the expected value of the output power in the predicted scenario of the wind farm; P_d indicates the active power of the load when considering the frequency and voltage response characteristics; N_D denotes the set of loads.

2) The voltage response constraints of the load frequency:

$$P_d = P_d^N \cdot \left\{ \left[\alpha_Z \cdot \left(\frac{V_t}{V_N} \right)^2 + \alpha_I \cdot \frac{V_t}{V_N} + \alpha_P \right] \cdot \left(1 + \Delta f \cdot \beta_d \right) \right\} \tag{3}$$

where P_d^N indicates the expected value of the load power; the static characteristics of the load are expressed by a ZIP model; P_Z, P_I, and P_P represent the load ratios at the constant impedance, constant current and constant power respectively; β_d indicates the coefficient of increase or decrease of the active power of the load resulting from generation unit frequency changes.

3) The upper and lower limits of the output power of the generator set:

$$P_g = P_g^0 + \Delta f \cdot \beta_g \tag{4}$$

$$\underline{P}_g \le P_g^0 \le \overline{P}_g \tag{5}$$

$$\underline{P}_g \le P_g \le \overline{P}_g \tag{6}$$

where P_g^0 indicates the base point of the output power of Generation unit g; Δf indicates the frequency deviation of the system, $\Delta f = f - f_N$; β_g indicates the coefficient of increase or decrease of the output power of Generation unit g resulting from generation unit frequency changes; $\overline{P}_g$ and $\underline{P}_g$ indicate the upper limit and the lower limit of the output power of Generation unit g.

4) Node voltage amplitude constraints:

$$\underline{V} \le V_t \le \overline{V} \tag{7}$$

$$\Delta \underline{f} \le \Delta f \le \Delta \overline{f} \tag{8}$$

where $\overline{V}$ and $\underline{V}$ indicate the upper and lower limits of the voltage amplitude; $\Delta \overline{f}$ and $\Delta \underline{f}$ indicate the upper and lower deviation limits of the frequency.

Constraints for random scenarios s:

1) Power balance constraints:

$$\sum_{g\in N_G} P_{g,s} + \sum_{w\in N_W} P_{w,s} = \sum_{d\in N_D} P_{d,s}, \forall s \in N_S \tag{9}$$

where $P_{g,t,s}$ indicates the output power of Generation unit g during Period t in the error scenario s; $P_{w,t,s}$ indicates the output power during period t in the error scenario s of the wind farm; $P_{d,t,s}$ indicates the active power of the load when considering the frequency and voltage response characteristics during Period t in the error scenario s; N_S represents the set of random scenarios for wind farm.

2) The voltage response constraints of the power generation and the load frequency:

$$\begin{cases} P_{g,s} = P_{g,s}^0 + \Delta f_s \cdot \beta_g \\ P_{d,s} = P_d^N \cdot \left\{ \left[\alpha_Z \cdot \left(\frac{V_{t,s}}{V_N} \right)^2 + \alpha_I \cdot \frac{V_{t,s}}{V_N} + \alpha_P \right] \cdot \left(1 + \Delta f_s \cdot \beta_d \right) \right\} \end{cases} \tag{10}$$

where $P_{g,s}^{0}$ indicates the base point of the output power of generation unit g in the error scenario s; Δf_s indicates the frequency deviation in the error scenario s; V_s indicates the voltage of the load in the error scenario s.

3) The upper and lower limits of the output power of the generator set:

$$\underline{P}_g \le P_{g,s}^{0} \le \overline{P}_g \tag{11}$$

$$\underline{P}_g \le P_{g,s} \le \overline{P}_g \tag{12}$$

4) The reserve capacity constraints adjusted from the predicted scenario to the error scenario s:

$$P_{g,s}^{0} - P_g^{0} \le R_g^{U} \tag{13}$$

$$P_g^{0} - P_{g,s}^{0} \le R_g^{D} \tag{14}$$

$$R_g^{U} \le \overline{R}_g^{U} \tag{15}$$

$$R_g^{D} \le \overline{R}_g^{D} \tag{16}$$

5) Power curtailment constraint of wind farm:

$$\sum_{w \in N_W} \sum_{s \in N_S} \Delta P_{w,s} \le \rho \cdot \sum_{w \in N_W} \sum_{s \in N_S} P_{w,s} \tag{17}$$

$$0 \le \Delta P_{w,s} \le P_{w,s}, \forall w \in N_W, \forall s \in N_S \tag{18}$$

where ρ is the maximum allowable wind power curtailment rate setting.

6) Node voltage amplitude constraints:

$$\underline{V} \le V_{d,s} \le \overline{V} \tag{19}$$

$$\Delta \underline{f} \le \Delta f_s \le \Delta \overline{f} \tag{20}$$

Equations (1) ~ (20) constitute the frequency-voltage characteristics concerned optimal dispatch model, which is mathematically a nonlinear programming model, which is solved by the technically mature GAMS platform [15] in this paper.

The major difference between the above-mentioned model and the traditional dispatching model is the static response characteristics of the frequency and voltage considering the power generation and load, so the above-mentioned model has the potential of collaborative dispatching.

A penalty term of the deviation of the frequency and voltage is introduced into the objective function to avoid reducing power generation cost in the predicted scenario by reducing load demands through voltage and frequency reduction. The collaborative capacity may alleviate the demands of the ramp rate between periods in the predicted scenario.

The advantage of the power generation from renewable energies during the collaborative dispatching mainly reflects that when the renewable energy generation power fluctuates and happens in the error scenario, the driving and braking power can be adjusted at the power generation & consumption terminal of the power system based on the increase or decrease in electric power by adjusting the voltage and frequency. Thus, it is more conducive to achieving source balance and expanding operation.

Firstly, when the frequency and voltage is allowed to vary within in a certain range, the power generation from renewable energies is not at the expense of the grid quality, but is to explore the potential of the inherent response characteristics when the power generation and load vary with the frequency and voltage within the allowable fluctuation range of the frequency and voltage.

Secondly, the power generation from renewable energies using the frequency-voltage characteristics has a large available space and a wide range of operation. As the power grid is continuously extended, the potential of renewable energy generation through the grid is also increased correspondingly. Thus, all power grids are applicable. However, the construction of hydropower plants and pumped-storage power stations is restricted by geographical conditions, and now the capacity of the energy storage equipment is generally not large.

Finally, compared with the demand-side management technology, the potential to explore the frequency characteristics neither need changing the mode of consumption nor affect the normal operation of electrical equipment [16]. The demand-side management technology often only involves a small number of users who have signed an agreement with the grid company which needs to give a certain amount of compensation, while the potential to explore the grid quality involves most users.

3. Case study

Case studies are conducted on an actual example of provincial power grid. The static load models commonly used by the grid planning and dispatching departments at levels include 40% constant impedance +60% constant power, 30% constant impedance +40% constant current +30% constant power or 30% constant impedance +30% constant current +40% constant power [17]. In general, the LDP value is 1.2% or 1.8%. Accordingly, Table 1 shows the impact of the changes in voltage and frequency on the active power consumption of the load when the LDP is set to 3.1% in the case of ratios of P1, P2, and P3.

Table 1. Impact of the changes in voltage and frequency on the active power consumption of the load

Load ratios at the constant impedance, constant current and constant power	The change in the active power of the load (%) when the voltage increases by 5% and the frequency increases by 0.2%	The change in the active power of the load (%) when the voltage is reduced by 5% and the frequency is reduced by 0.2%
40% constant impedance +60% constant power	4.75%	-4.50%
30% constant impedance +40% constant current +30% constant power	5.73%	-5.51%
30% constant impedance +30% constant current +40% constant power	5.22%	-5.02%

As is shown in Table 1, the active power of the load on the system can be adjusted obviously only by adjusting the voltage and frequency within the allowable grid quality, which is obviously very beneficial for the renewable energy generation.

The primary frequency modulation function of the conventional generator set can automatically adjust the generator output power when the system frequency changes. That is, when the frequency is higher than the rated frequency (regardless of dead zone), the primary frequency modulation function of the generator will automatically reduce the generator output power, according to the set adjustment coefficient, while the generator output power will be increased automatically when the frequency is lower than the rated frequency.

For one of provincial power grids in China, the overall installed capacity is calculated at 70 million kilowatts, the installed capacity of the wind power is 6.7 million kilowatts, and the maximum load of the entire grid is 62.5 million kilowatts. The provincial power grid experiment shows that the measured curve is well consistent with the simulation curve when LDP=3.1%. The commonly-used static load models are analysed.

(1) The static load model adopts 40% constant impedance +60% constant power. Ideally, the load power in the power grid increases by 2.969 million kilowatts, equivalent to the consumption of additional 2.969 million kilowatts of wind power, when the power supply voltage of all loads in the power grid increases by 5% and the system frequency increases by 0.2%. Similarly, the load power in the power grid is reduced by 2.812 million kilowatts, which can effectively make up for the insufficient wind power output, when the load supply voltage is reduced by 5% and the system frequency is reduced by 0.2%.

(2) The static load model adopts 30% constant impedance +40% constant current +30% constant power. Ideally, the load power in the power grid increases by 3.581 million kilowatts, equivalent to the consumption of additional 3.581 million kilowatts of wind power, when the power supply voltage of all loads in the power grid increases by 5% and the system frequency increases by 0.2%. Similarly, the load power in the power grid is reduced by 3.443 million kilowatts, which can effectively make up for the insufficient wind power output, when the load supply voltage is reduced by 5% and the system frequency is reduced by 0.2%.

(3) The static load model adopts 30% constant impedance +30% constant current +40% constant power. Ideally, the load power in the power grid increases by 3.262 million kilowatts, equivalent to the consumption of additional 3.262 million kilowatts of wind power, when the power supply voltage of all loads in the power grid increases by 5% and the system frequency increases by 0.2%. Similarly, the load power in the power grid is reduced by 3.137 million kilowatts, which can effectively make up for the insufficient wind power output, when the load supply voltage is reduced by 5% and the system frequency is reduced by 0.2%.

4. Conclusion

In order to deal with the wind power curtailment problem, the frequency-voltage characteristics concerned optimal dispatch for power system with large-scale wind power integration is proposed in this paper. Through integration of the optimization of frequency characteristics and voltage characteristics into the traditional power system economic dispatch model, the flexibility resources of generation side and load sides in power systems are mobilized to promote large-scale wind power accommodation. The numerical analysis for an actual provincial power grid indicates that the proposed frequency-voltage characteristics concerned optimal dispatch method can promote wind power utilization efficiency and improve the economy of power system operation.

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