Optimization Scheduling Model for Wind-thermal Power System Considering the Dynamic penalty factor

Siyu PENG1, Jianchun LUO2, Yunyu WANG2, Jun YANG2, Hong RAN2, Xiaodong PENG2, Ming HUANG2, Wanyu LIU3

1. State Grid Chongqing Electric Power Co. Qi’nan Power Supply Branch Company, 401420 Chongqing, China
2. State Grid Chongqing Electric Power Co. Wulong Power Supply Branch Company, 408500 Chongqing, China
3. School of Electrical Engineering and Information, Sichuan University, 610065 Chengdu, China

Email: 370379904@qq.com

Abstract. In this paper, a new dynamic economic dispatch model for power system is presented. Objective function of the proposed model presents a major novelty in the dynamic economic dispatch including wind farm: introduced the “Dynamic penalty factor”. This factor could be computed by using fuzzy logic considering both the variable nature of active wind power and power demand, and it could change the wind curtailment cost according to the different state of the power system. Case studies were carried out on the IEEE30 system. Results show that the proposed optimization model could mitigate the wind curtailment and the total cost effectively, demonstrate the validity and effectiveness of the proposed model.

1. Introduction

With more and more large-scale wind farms integrated into power system, the uncertainty and volatility the wind power brings have caused many problems. Thus, how to reduce the wind curtailment is an important question[1-2]. In recent years, wind curtailment has become one of important factors restricting the development of wind power[3].

When system transmission capacity is enough, the wind curtailment is closely related to the active wind power and the power demand. To reduce the wind curtailment, extensive and deep researches have been carried on. And in most literature this problem was solved by considering the wind curtailment cost, but all the penalty factor introduced in the objective function is a fixed value[4]. All the methods do not consider the influence that the uncertainty and volatility the wind power brings, and they also don’t consider the impact that the power demand brings to the power system. Cause the active wind power and the power demand is highly volatility, using the fixed wind curtailment penalty factor may influence the objectivity of the dynamic economic dispatch including the wind farm.

Thus, this paper introduces a new definition, namely “dynamic penalty factor”. This factor considers the uncertainty of the active wind power and power demand comprehensively, and gets its value through the fuzzy logic. The penalty factor could change the wind curtailment cost according to the current state of the system so that to change the active wind power. And on this basis, this paper built an optimization scheduling model for wind-thermal power system considering the dynamic penalty factor. Finally, simulations were carried out with the modified IEEE 30-bus system using the cuckoo search optimization algorithm[5]. The results demonstrate the validity and effectiveness of the proposed model.
2. Dynamic penalty factor

2.1 Determination of the dynamic penalty factor
In high wind density region, wind power generation is of good support to the power system, especially at high demand situations. This support of wind power depends on the active wind power and the power demand of the system. Hence, the economic dispatch model needs some factors in addition to account for the support of wind energy while handling different situations of power demand scenarios. In order to manage such a situation, this paper introduces a new coefficient—“dynamic penalty factor”, and its value depends on the active wind power and power demand, so it could influence the current state of the system.

2.2 Fuzzy logic
Both, power demand and wind velocity exhibit non-linear characteristics due to their uncertainty. They should therefore be presented as fuzzy quantities. Three variables are considered as fuzzy variables. They are active wind power, power demand and dynamic penalty factor.

For the design of dynamic cost coefficient, fuzzy logic[6] model implementation is shown in Fig. 1.

Figure 1. Fuzzy logic model of dynamic penalty factor

2.3 Demarcation for fuzzy parameters
In this model, three linguistic terms (e.g. high, low, medium) referred to as fuzzy set, are assigned to power demand, active wind power and dynamic penalty factor. The membership function of each variable are shown as follows:

(a) Power demand

Figure 2. The membership function of the power demand
Where \( L_h \) is minimum power demand and ‘a’ is upper limit of low power demand. ‘b’ is lower limit of medium power demand and ‘c’ is upper limit of medium power demand. \( L_e \) is maximum power demand and ‘d’ is lower limit of high power demand.

(b) Active wind power
Figure 3. The membership function of the active wind power

Where $A_l$ is minimum active wind power and ‘a’ is upper limit of low active wind power. ‘b’ is lower limit of medium active wind power and ‘c’ is upper limit of medium active wind power. $A_h$ is maximum active wind power and ‘d’ is lower limit of high active wind power.

(3) Dynamic penalty factor

Figure 4. The membership function of the dynamic penalty factor

Where $D_l$ is minimum dynamic penalty factor and ‘a’ is upper limit of low dynamic penalty factor. ‘b’ is lower limit of medium dynamic penalty factor and ‘c’ is upper limit of medium dynamic penalty factor. $D_h$ is maximum dynamic penalty factor and ‘d’ is lower limit of high dynamic penalty factor.

2.4 Fuzzy rules

Case 1: When power demand is low, the wind curtailment is the only choice when the absorption capacity of the system is limited. Thus, whatever the active wind power is high or low, the value of the dynamic penalty factor is low.

Case 2: When the power demand is medium, system needs the support from wind farms, and in order to absorb wind power as much as possible, the value of the dynamic penalty factor is medium. But when the active wind power is very high and system could not absorb so much wind power, wind curtailment is the only choice, so the value will decrease while the active wind power increase.

Case 3: When the power demand is high, wind power will be a good support to the system, even if the active wind power is low. So in order to decrease the wind curtailment, the value of the dynamic penalty factor is high.

Table 1 shows a summary of the result from fuzzy logic system.

Table 1. Fuzzy rules

| Power demand | Active wind power |
|--------------|-------------------|
|              | L     | M     | H     |
| L            | L     | L     | L     |
| M            | M     | —     | L     |
| H            | H     | —     | M     |

3. Wind-thermal coordination optimization model

3.1 Objective function

With large scale wind farms integrated into power system, this paper builds the wind-thermal optimization model, considering power demand and active wind power comprehensively by
introducing the dynamic penalty factor, and taking wind curtailment cost as one of the economic indicators, the objective function is as follows:

$$
\min F_T = \sum_{i=1}^{TNG} \left( \sum_{i=1}^{NG} f_c \left[ P_i(t) \right] + \sum_{j=1}^{NW} f_c \left[ P_j(t) \right] \right)
$$

(1)

Where $F_T$ is the total cost of the power system generation including thermal and wind powered generators; $NG$ is the number of thermal generators; $NW$ is the number of wind powered generators; $P_i(t)$ is the power generated from bus $i$ (thermal generator); $f_c \left[ P_i(t) \right]$ is the cost of thermal power generation $P_i$; $P_j(t)$ is the power generated from bus $j$ (wind powered generator); $f_c \left[ P_j(t) \right]$ is the cost of wind power generation $P_j$.

Fuel cost of the thermal generators is as follows:

$$
f_c \left[ P_i(t) \right] = a_i P_i^2(t) + b_i P_i(t) + c_i
$$

(2)

where $a_i$, $b_i$, and $c_i$ are constants of the fuel cost function.

Cost of the wind power generation is as follows:

$$
f_c \left[ P_j(t) \right] = d(t) \xi \left[ P_{nj}(t) - P_j(t) \right]
$$

(3)

Where $\xi$ is the wind curtailment coefficient; $P_{nj}(t)$ is the predicted power of wind generator $j$ for the time interval $t$; $d(t)$ is the dynamic penalty factor for the time interval $t$.

Subject to

(1) Real power balance constraint

$$
\sum_{i=1}^{NG} P_i(t) + \sum_{j=1}^{NW} P_j(t) + P_{loss}(t) = P_t(t), \ t = 1, 2, \ldots, T
$$

(4)

Where $P_t(t)$ is the load forecasting for the time interval $t$; $P_{loss}(t)$ is the transmission losses that take place in the system during the time interval $t$.

(2) Real power operating limits

$$
\underline{P}_i \leq P_i(t) \leq \bar{P}_i, \ i \in NG, \ t = 1, 2, \ldots, T
$$

(5)

Where $\underline{P}_i$ and $\bar{P}_i$ are the minimum and the maximum real power outputs of $i$th thermal generator, respectively.

(3) Total actual wind power generation limit

$$
0 \leq P_j(t) \leq \bar{P}_w(t), \ t = 1, 2, \ldots, T
$$

(6)

Where $\bar{P}_w$ is the predicted active wind power.

(4) Ramp up/down constraints

$$
\begin{align*}
\left| P_i(t) - P_i(t-1) \right| & \leq \eta_1 \Delta T, \ i \in I, \ t = 1, 2, \ldots, T \\
\left| P_i(t-1) - P_i(t) \right| & \leq \eta_2 \Delta T
\end{align*}
$$

(7)

Where $P_i(t-1)$ is the power generated from bus $i$ (thermal generator) for the time interval $t-1$; $\eta_1$ and $\eta_2$ are the maximum ramping up rate and the maximum ramping down rate during normal operation of the $i$th thermal generator, respectively;

4. Methodology

4.1 The impact of the dynamic penalty factor on the wind curtailment
The cuckoo search optimization algorithm is adopted to solve equations established by objective function and constraints. IEEE30 system is used as the example system in this paper. The system includes 3 thermal units and 3 wind farms (A, B, C), and the installed capacity of 3 wind farms are all 50MW. Wind curtailment coefficient $\xi$ is 975yuan/(MWh), $v_{in}$, $v_{N}$, $v_{out}$ are 3.5, 13, 25m/s respectively. In order to compare the 2 cases of with or without the dynamic penalty factor, simulations were carried out and the results show that after considering the dynamic penalty factor, there is a clearly decrease in the wind curtailment and the total operating cost.

![Wind curtailment in three wind farms](image)

**Figure 5** Wind curtailment in three wind farms

**Figure 6** Comparison of the power system total cost

The simulation results is shown in fig.5 and fig.6, and according to it, the wind curtailment has a obvious decrease after considering the dynamic penalty factor. And the wind curtailment of wind farm B is decreased to 0. The total cost of the system also decreased after considering the dynamic penalty factor when there is wind curtailment, and the decrease could up to 7.74% at most.

5. **Conclusion**

(1) The dynamic penalty factor will be changed with the power demand and the active wind power, so it could adjust its value in real time to change the wind curtailment cost.

(2) The introduction of the dynamic penalty factor could decrease the wind curtailment and the total operating cost effectively.

But the value of the dynamic penalty factor is subjective to some extent, and some limiting factor such as the environmental effect is important to the wind curtailment. So, how to make the value of the dynamic penalty factor more objective, and take the above factors into account in the model will be the follow-up research content.

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