A novel power system operation simulation method considering multi-state models of coal-fired power unit: a case study of coal-fired power transformation in a certain region of China

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Abstract. Coal-fired power has played an important role in the power systems, but its operational characteristics, especially the flexibility characteristics is modelled relatively simple in the current operation simulations. Given the background of a rapid development of renewable energy and a sustainable transformation of power systems in China, it is essential to build a refined model of coal-fired power units that can be incorporated into an operation simulation method. First, this study provides an analysis on the flexibility characteristics of coal-fired power units, including the minimum stable output, ramp limit and minimum up/down time. Subsequently, a multi-state probabilistic model of coal-fired power units is proposed. This study also constructs a sequential operation simulation method based on the universal generation function (UGF) method that incorporates multiple states of coal-fired power units. Finally, this study provides a development and transformation pathway for coal-fired power plants in the North Hebei (NH) region and suggestions for promoting a sustainable development of the power system based on the proposed method and multi-state model.

1. Introduction

By the end of 2018, the total installed capacity of wind power and photovoltaic power generation in China has exceeded 360 GW, ranking first in the world. However, it is a challenge to accommodate large-scale renewable energy due to the inherent volatility and uncertainty of renewable energy sources [1]. Power system flexibility becomes the key to the sustainable development of modern power systems with the explosive growth of renewable capacities. As the major conventional power generation type in China, coal-fired power not only accounts for more than 50% of the installed capacity, but also is the main source for power systems regulation, which provides flexibility to help integrating renewable power. China’s coal-fired power units are gradually transforming from undertaking base load to providing power systems flexible regulation capacity. Therefore, it is urgent to explore the considerate operation simulation method of coal-fired power to facilitate its new role in the operation, which can not only effectively reflect the operation situation of coal-fired power in...
power systems, but also better analyze the issues such as coal-fired power transformation and study the measures to promote the sustainable development of power systems.

There are mainly two power system operation simulation methods, i.e., the probabilistic production simulation (PPS) and the sequential production simulation (SPS) [2, 3]. As a non-sequential method, the PPS method has been widely used in reliability and generation adequacy analysis [4]. Reference [3] proposes a PPS model to evaluate the wind energy curtailment during the heat supply period. In Reference [5], a PPS method is built for system planning and consumption assessment in the medium and long-term time scale. Reference [6] proposes an improved PPS method to facilitate the cost-benefit analysis of pumped hydro storage. For the SPS method, the unit commitment and/or economic dispatch (UCED) are mainly utilized [7-9]. In Reference [10], the maximum wind and solar power integration capacity is simultaneously calculated based on an enhanced SPS in consideration of several boundary conditions of Shaanxi power system such as power supply, network constraints and future load. Reference [11] uses typical scenario methods to do the SPS. In summary, the PPS is a non-sequential method and its results cannot reflect sequential characteristics of the power system. On the contrary, the SPS method can include sequential characteristics of power system, but it requires the time series data set that includes the sequential data of generation output, electricity demand, and the states of all available generating units for each period of time, and these data are difficult to obtain, especially for the medium and long term. By applying typical scenarios, the simulations could provide better overview, however, it is another difficult problem how to choose scenarios [12]. The computation complexity of the SPS (or UCED) is also one of the difficulties for operation simulation [3]. In addition to above methods, the universal generating function (UGF) based simulation methods are also applied to power system operation simulation in recent years [13, 14]. In Reference [15], an extended UGF based on belief function theory is introduced to conduct the reliability analysis of multi-state systems with epistemic uncertainty. The reliability evaluation model of the integrated gas and power systems is constructed in Reference [16] based on the UGF techniques. In conclusion, it can be found that the UGF method can easily consider a large number of uncertainties and achieve operation simulation with high efficiency. However, the uncertainties of coal-fired power unit states are insufficiently considered in current studies and more servable information should be mined to better support the study such as coal-fired power transformation.

To address the concerns above and dedicated to analyzing the influence of coal-fired power units at the same time, this study builds the multi-state probabilistic models of base-load coal-fired power units and peaking coal-fired power units, and also considers the dynamic transition of states. Based on these models, an improved operation simulation method based on the UGF is constructed, which considers the uncertainties of the operation states of coal-fired power units, as well as efficiently realizes the sequential simulation of power systems. By combining the established coal-fired power models with the sequential operation simulation method, this study takes the Northern Hebei (NH) region as an example, analyzes the current weak links of power system operation in this region and the benefits for increasing flexibility of coal-fired power units. Based on the simulation results, this study puts forward the coal-fired power transformation development pathway for this region.

2. Power system operation simulation method considering multi-state probability models of coal-fired power units

2.1. Multi-state modelling of coal-fired power units
Multi-state analysis method is an important method of uncertain analysis [17]. This study introduces the multi-state analysis method to establish multi-state probability models for base-load units and peaking units according to the different tasks undertaken by coal-fired power units.

2.1.1. Model of base-load units. The base-load units have a weak regulation ability, usually running at rated power, or sometimes outage due to failure. Therefore, this study establishes a 2-state probabilistic model of base-load units, as shown in Eq. (1).
where, $P_{i,t}$ is the output of base-load unit $i$ at time $t$, $P_i^N$ is the rate power of base-load unit $i$, $P_{ro,i,t}$ is the probability of each state happening at time $t$, $P_i^{FOR}$ is the forced outage rate.

2.1.2. Model of peaking units. According to the needs of power systems, the peaking units used for peak regulation has 7 operating states, including planned outage, forced outage, ramp up, ramp down, derating and rated. In addition, with the change of power demand, there are dynamic transitions between each state. When the power demand decreases, the peaking units will reduce their output, and their operating states will also be transferred from the rated or derating state with larger output to the derating or outage state. On the contrary, when the power demand increases, the operating state of the peaking units will also be transferred from the planned outage or derating state to the derating or rated state. At the same time, the units can also be forced outage due to failure. Based on this process, this study introduces the 7-state probabilistic model of the peaking units, and their state transition equation is shown in Eq. (2).

$$M_{i} = \begin{bmatrix}
\rho_{i} & 0 & 0 & 0 & \rho_{i} & 0 & 0 \\
\rho_{i} & 0 & 0 & 0 & \rho_{i} & 0 & 0 \\
\rho_{i} & 0 & 1-(\rho_{i}+\rho_{2}+\lambda_0) & \lambda_0 & 0 & 0 & \rho_{2} \\
0 & \rho_{i} & 1-(\rho_{i}+\mu_{1}+\mu_{2}) & \mu_{1} & 0 & \mu_{2} & 0 \\
0 & \rho_{i} & 0 & 1-(\rho_{i}+\frac{1}{T_{R1}}) & 0 & 0 & 0 \\
0 & 0 & \rho_{i} & \lambda_0 & 0 & 1-(\rho_{i}+\lambda_0) & 0 \\
0 & 0 & 0 & 0 & 1-(\rho_{i}+\frac{1}{T_{R2}}) & 1-(\rho_{i}+\frac{1}{T_{R2}}) & 0
\end{bmatrix}$$

(3)

where $\rho_{i1}$ and $\rho_{i2}$ denote the necessary and unnecessary rate of derating state respectively. $\rho_{i2}$ and $\rho_{i}$ denote the necessary and unnecessary rate of rated state respectively. $\lambda_0$ and $\mu_{i}$ denote the fault and repaired rate of rated state respectively. $\lambda_0$ and $\mu_{2}$ denote the fault and repaired rate of derating state respectively. $T_{R1}$ and $T_{R2}$ denote the ramp time of ramp state 1 (from planned outage state to derating state) and the ramp time of ramp state 2 (from derating state to rated state).

To simplify computation, the outage states and ramp state 1 which have the same value can be merged into an equivalent state, and the derating state and ramp state 2 that have the same value can also be merged. As a result, the 7-state probabilistic model of peaking units is as Eq. (4).

$$P_{i,t} = \begin{cases}
P_{i,t}^{0} = P_{i,t}^{DC} = P_{i,t}^{ON} + P_{i,t}^{DC} + P_{i,t}^{RO} + P_{i,t}^{FOR} \\
P_{i,t}^{1} = P_{i,t}^{DC} = P_{i,t}^{ON} + P_{i,t}^{DC} + P_{i,t}^{RO} + P_{i,t}^{FOR} \\
P_{i,t}^{2} = P_{i,t}^{DC} = P_{i,t}^{ON} + P_{i,t}^{DC} + P_{i,t}^{RO} + P_{i,t}^{FOR}
\end{cases}$$

(4)

where $P_{i,t}$ is the output of peaking unit $i$ at time $t$, $P_i^N$ is the rate power of peaking unit $i$, $P_{ro,i,t}$ is the probability of each state happening at time $t$, $P_{i}^{FOR}$ is the output of peaking unit $i$ under derating state.
2.2. Power system operation simulation method based on the UGF model

Power system operation simulation is an important method in the research of coal-fired power transformation. In order to better reflect the operation of coal-fired power units, a sequential operation simulation method of power systems considering multiple states of coal-fired power units is established based on the multi-state probabilistic models proposed in the previous section.

First, this study establishes the corresponding UGF according to the probability distribution of the operation state of coal-fired power units and other components of the power system. Then, by using the multiplication of the UGF, the states of coal-fired power units and other components are matched freely, and then the joint probability distribution of the power system is calculated. Finally, the output of each unit can be calculated by matching the supply and demand of the calculated joint probability distribution with the power load in this period. Taking time period \( t \) as an example, the calculation method of joint probability distribution of the power system with \( m \) power units is shown in Eq. (5).

\[
\begin{align*}
    u_{t}^{\text{sys}} &= \bigotimes \{ u_{t}^{1}, u_{t}^{2}, \ldots, u_{t}^{m} \} = \sum_{k=1}^{n_{\text{sys}}} p_{m,k,t}^{\text{sys}} \cdot z_{r,o}^{k} \\
\end{align*}
\]  

where \( u_{t}^{\text{sys}} \) denotes the UGF of joint probability distribution of power system. \( \bigotimes \) denotes the multiplication of UGF. \( u_{t}^{m} \) denotes the UGF of unit \( m \). \( n_{\text{sys}} \) denotes state number of joint probability distribution. \( p_{m,k,t}^{\text{sys}} \) and \( p_{r,o}^{k} \) denote the \( k \)-th output state and corresponding probability of power system. In addition to coal-fired power units, nuclear power units and conventional hydropower units are considered according to the 2-state model with the rated and outage. The model of gas-fired power units is established by reference to the peak units. Wind power output is subject to Weibull distribution, and solar output is subject to Beta output. The two processes of the pumped storage plant, namely energy storage and power generation, are also considered.

By comparing each output state \( p_{r,o}^{k} \) with load \( L_{t} \), and counting these states whose output is less than load, the reliability indices such as loss of load probability (LOLP) and expected energy not supply (EENS) of subsystem become available. When a new unit is put into operation, the change of EENS is the unit’s expected generating capacity. Reliability indices of subsystem can be calculated as Eq. (6) and Eq. (7).

\[
\begin{align*}
    \text{LOLP}_{m} &= \sum_{r \in C_{L}} p_{r,o}^{m} \\
    \text{EENS}_{m} &= \sum_{r \in C_{L}} p_{r,o}^{m} [L_{t} - p_{r,o}^{m}] \Delta t \\
\end{align*}
\]  

On this foundation, putting the \( m+1 \)th unit into operation, the expected generating energy of this unit can formulate as Eq. (8).

\[
\begin{align*}
    E_{m+1,t} = \text{EENS}_{m,t} - \text{EENS}_{m+1,t} \\
    E_{1,t} = L_{t} - \text{EENS}_{1,t} \\
\end{align*}
\]  

In particularly, the expected generating energy of the first unit is as Eq. (9).

The joint distribution of the system after putting new units into operation is continuously calculated, and Eqs. (5) - (9) are used to calculate the expected generating capacity and system reliability of each unit in time period \( t \). When all units are put into operation, the power system reliability and other indexes of all units under this period can be obtained. If the above process is repeated for different time periods, the operation condition and reliability of the unit within the whole study period can be obtained. For the whole study period, LOLP of the power system is the average LOLP of each time period, and EENS is the sum of EENS of each time period.

2.3. Evaluation index of power system operation

This study introduces a number of indices, including loss of load probability (LOLP), probability of insufficient upward flexibility (PIUF), probability of insufficient downward flexibility (PIDF), and wind and solar curtailment rates. By comparing changes of the indices before and after coal-fired
power transformation, the impacts of coal-fired power units on system operation can be obtained, as well as of its role in the sustainable development of power system.

LOLP is a key index for evaluating power system reliability and it mainly refers to the probability that a system’s power generation capacity is unable to meet the load during the time window.

PIUF refers to the probability of a power system not being able to increase its output through upward flexibility adjustments in a pre-set mode and within a certain time scale (e.g. 15 minutes, 30 minutes, and 1 hour) to cope with uncertainty factors such as power system component failure and sudden increase in load. PIDF refers to refers to the probability of a power system not being able to decrease its output through downward flexibility adjustments in a pre-set mode and within a certain time scale to cope with uncertainty factors such as sudden increase in renewable energy output. The calculation methods of these two indicators are shown in Eq. (10) and Eq. (11), respectively.

\[
P_{\text{LOLP}} = \sum_{n,k,t} P_{\text{up},n,k,t} \cdot P_{\text{load},n,k,t} \]

\[
P_{\text{LOLP}} = \sum_{n,k,t} P_{\text{down},n,k,t} \cdot P_{\text{load},n,k,t} \]

where \( I_{\text{up},n,k,t} \) and \( I_{\text{down},n,k,t} \) represent the \( l \)-th state value of the upward and downward adjustment range of the power system with \( n \) units, respectively. \( \Delta P_{\text{up},n,k,t} \) and \( \Delta P_{\text{down},n,k,t} \) represent the \( k \)-th state value of the upward and downward adjustment range of the power system with \( n \) units, respectively.

The wind curtailment rate and solar curtailment rate can be calculated by Eq. (12) and Eq. (13), respectively.

\[
W_{\text{CR}} = 1 - \sum_{i \in W} \sum_{t=1}^{T} E_{i,t} / \sum_{i \in W} \sum_{t=1}^{T} \sum_{k=1}^{N_i} P_{i,k,t} \cdot p_{i,k,t} \]

\[
S_{\text{CR}} = 1 - \sum_{i \in S} \sum_{t=1}^{T} E_{i,t} / \sum_{i \in S} \sum_{t=1}^{T} \sum_{k=1}^{N_i} P_{i,k,t} \cdot p_{i,k,t} \]

where \( W_{\text{CR}} \) and \( S_{\text{CR}} \) are wind curtailment rate and solar curtailment rate, respectively. \( W \) and \( S \) are the set of wind power units and the set of solar power units, respectively. \( T \) is the time period considered. \( N_i \) is the number of states for unit \( i \). \( p_{i,k,t} \) and \( p_{i,k,t} \) are the \( k \)-th output state and its probability of unit \( i \) at time \( t \), respectively.

3. Simulation process

Based on the UGF, the improved operation simulation method considering multi-state probabilistic models of coal-fired power units is obtained, and its main process shown in Figure 1 is as follows.

Step 1: Import original data and build the UGF of power units.

Step 2: Put each unit successively, and then calculate the initial joint distribution in the first period by the UGF based operation simulation method.

Step 3: Compare the expected generation energy of all units with load demand. Calculate its charging capacity because the energy storage facility is equivalent to the load when the sum of expected power generation of each unit is greater than the load. Calculate its discharge capacity by establishing the model of peaking unit for energy storage because the energy storage facility is equivalent to a unit when the sum of expected power generation of each unit is greater than the load. When the sum of the expected generation capacity of each unit equals the load, the energy storage neither charges nor discharges.

Step 4: Complete the operation simulation of this period, and calculate the indices in this period.

Step 5: Repeat step 2 to step 4, until all time periods are considered.

Step 6: Calculate indices of the whole research cycle.
Input load data, parameters needed for modeling, total number of units \( N \), research cycle \( T \), etc.

Initialize unit number \( n = 1 \) and simulation period \( t = 1 \).

Calculate UGF of system containing the first \( m \) units \( u(m,t) \) by (5).

Initialize UGF of system \( u(0,t) = 1 \).

Calculate expected energy generation of unit \( n \) \( E(m,t) \) by (6)-(9).

\( m = N ? \)

Calculate expected energy generation of unit all units and judge the working state of energy storage.

\( t = T ? \)

Calculate evaluating indices by (6) and (10)-(13).

Calculate evaluating indices of the entire period.

End.

Figure 1. Process of the improved operation simulation.

4. Empirical results and discussion

This section presents the simulation of the power system operation in the NH region in 2018 with the focus on several weak connections. Given the simulation results, the benefits by having flexible coal-fired power units are analyzed. The basic information of the NH region is shown in Table 1. The algorithm in this study is implemented on MATLAB 9.4, and the computing platform is Dell P5820x (CPU: I9-9900x, memory: 64GB).

Through both software upgrading of the control system and technical retrofit of equipment, namely, thermoelectric decoupling, low voltage steady combustion and other technical retrofit, the flexibility improvement of a coal-fired power plant can be realized. This study explores the influence of flexibility improvement by comparing evaluation metrics before and after the flexibility transformation.

Table 1. Basic information of NH power system in 2018.

| Installed Capacity (GW) | Proportion (%) | Generation Energy (TWh) | Utilization Hours (hr) |
|------------------------|---------------|-------------------------|------------------------|
| Hydro                  | 0.42          | 1.17                    | 0.58                   | 1380.95                |
| Coal-fire              | 16.87         | 46.98                   | 73.65                  | 4365.74                |
| Wind                   | 12.44         | 34.64                   | 26.49                  | 2129.42                |
| Solar                  | 6.18          | 17.21                   | 6.78                   | 1097.09                |
| **Total**              | **35.91**     | **100.00**              | **107.50**             | -                      |
4.1. NH power system operation simulation

The indices related to power system’s annual flexibility and reliability in the NH region are shown in Table 2. In terms of flexibility, the region’s PIUF is 4.22E-07%, at a relatively low level, which indicate sufficient upward flexibility; its PIDF reaches 67.52%, which suggest severely insufficient downward flexibility. In terms of reliability, the region’s LOLP is about 0.91%, and its expected time of power failure is 79.7 hours, which indicate a much higher level compared with the 2018 national average. In terms of wind and solar curtailment, the region’s wind and solar curtailment rates reached 6.79% and 4.19%, respectively, which indicate higher levels compared with national averages. Hence, there is still room for improvement in some aspects of the NH region’s power system, such as downward flexibility, power supply reliability and renewable energy utilization.

Table 2. Evaluation metrics for the NH region in 2018.

| PIUF (%) | PIDF (%) | LOLP (%) | Wind curtailment rate (%) | Solar curtailment rate (%) |
|----------|----------|----------|---------------------------|---------------------------|
| 4.22E-07 | 67.52    | 0.91     | 6.79                      | 4.19                      |

4.2. Benefit analysis of flexibility improvement of coal-fired power

To study the benefit for increasing the operational flexibility of coal-fired power units in the NH region, this study makes an analysis of how increased flexibility of coal-fired power units affects such indices as flexibility and reliability of the NH power system and what role it plays in promoting renewable energy integration when all technical measures reach international advanced levels. Considering that reducing a unit’s minimum stable output has the most significant effect on promoting renewable energy integration [18], the transformation needs to focus on lowering the minimum stable output level of pure condensing power units to 30%, and on lowering that of CHP units to 30% in summer and 40% of the rated capacity in winter. In addition, in view of the NH region’s actual situation, coal-fired power units are also improved to some degree in such aspects as overload capacity, ramp limit and minimum up/down time. Table 3 shows the results of various metrics of the power system after flexibility transformation.

Table 3. Evaluation metrics after coal-fired power flexibility transformation

| PIUF (%) | PIDF (%) | LOLP (%) | Wind curtailment rate (%) | Solar curtailment rate (%) |
|----------|----------|----------|---------------------------|---------------------------|
| 3.26E-13 | 3.59     | 1.16E-05 | 0.75                      | 0.06                      |

![Figure 2. PIDF for typical days before and after coal-fired power flexibility transformation.](image1)

![Figure 3. LOLP for typical days before and after coal-fired power flexibility transformation.](image2)
It can be seen from Table 2 that coal-fired power flexibility retrofitting has brought about some improvement in the NH power system’s upward flexibility and has been expected to contribute to a significant improvement in the region’s power supply reliability, which reducing its LOLP from 0.91% to 1.16E-05%. In the meantime, it also helps the power system a large improvement in its downward flexibility, namely, lowers the PIDF from 67.52% to 3.59% with a reduction of over 65 percentage points, so as to help the region effectively reduce its wind and solar curtailment rates, which are expected to decrease to 0.75% and 0.06%, respectively. In a nutshell, the coal-fired power flexibility retrofitting which has a huge benefit for application may help the NH region to significantly improve its power system flexibility and reliability and effectively promote renewable energy integration.

PIDF and LOLP for typical days before and after the retrofitting are shown in Figure 2 and Figure 3, respectively. As upward flexibility gets improved, LOLP of the NH region witnesses significant reduction in summer and winter, with the typical-day maximum LOLP dropping sharply from the pre-transformation level of 93.98% to the post-transformation level of 0.01%. The coal-fired power flexibility retrofitting will also help the NH region to greatly improve the power system’s downward flexibility in summer and winter, with the summer typical-day maximum LOLP from 85.96% to 1.21E-06%, and the winter typical-day maximum LOLP from 99.80% to 9.32E-11%. Hence, the coal-fired power flexibility transformation also provides an effective pathway for increasing system flexibility and reliability during high-risk periods, while reducing the risk of power curtailment and rationing during these periods.

Noting that the effect before and after the flexibility improvement is obvious, what more, we have been studying the cost of this improvement. Considering the length of the paper, we will explain this significant problem in the other paper.

5. Conclusions
Coal-fired power is still the most important source of power supply in China. Its development is challenged by the market competition and new demands from the system operational perspectives.

The NH grid is stepping into the stage with a high penetration of renewable energy installations, and the transformation of coal-fired power unit is of great value to promote the sustainable development of its power system. According to the quantitative analysis results of the model, the following suggestions against the NH region are obtained:

(1) According to the change of power supply and demand situation, a coal-fired power “storage” mechanism to maintain the flexible resource stock in NH region is worthwhile to be considered.

(2) It should accelerate the flexibility transformation of coal-fired power units in the NH region, and encourage coal-fired power units to add efficient thermal energy storage devices in combination with technological innovation, so as to adapt to the rapid fluctuation of power system load and renewable energy generation.

(3) Power supply of an CHP unit should not be bundled by its heat demand in areas with difficulty in peak load regulation of the power system. If it is really necessary to meet the heating demand through heat supply, the heat storage devices shall be installed synchronously to ensure the peak regulation safety of system.

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