New Energy Power System Coordination Simulation Method

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Abstract. The power system planning is of utmost significance for the grid’s safe, reliable, scientific and sustainable development. A scientific, refined, reasonable and adaptive scheme is of significant economic value and social value. The author made innovation based on the traditional operation analog model. Facing the massive new energy access issue, the author has established the intermittent and random new energy power system coordination operation simulation method that adequately reflect the new energy output. The study herein lays a theoretic and technological foundation for the optimal operation of future power system and the medium- and long-term sustainable development for energy.

1. Introduction

With incessant development of clean and green energy, the installed capacity of renewable energy such as wind power, photovoltaic is on increase. According to the statistics of the World Wind Energy Association (WWEA), the newly-added installed wind power in 2018 reached 53.9GW, and the cumulative installation was 600GW. And again, China's newly-added installed wind power reached 25.9GW, and the cumulative installation was 221GW. China is the world’s largest wind power market. According to statistics of the energy bureau, China's newly-added installed photovoltaic was over 44.26GW and the cumulative installation was over 174GW. According to the prevailing China's National Climate Change Programme, the non-fossil energy by 2020 would account for 15% of the primary energy consumption. According to the China-US Joint Announcement on Climate Change, China plans to raise the proportion of non-fossil energy in the primary energy consumption by around 20% by 2030.

In 2018, a province's new energy installed capacity reached 19GW, a year-on-year increase of 30%, and accounting for 21.8% of the total installed capacity. The province's new energy power generation was 30.628 billion kWh, a year-on-year increase of 40%, accounting for 10% of power generation. According to the province's relevant document, the proportion of non-fossil energy consumption by 2020 will increase to over 5%, and the installed new energy will account for around 35% of the province's total installed scale. The proportion will be up to 45%. To fulfill the above objective, the province will continue to significantly improve the proportion of the renewable energy in the energy mix.

In summary, new energy will achieve explosive growth in the future, which may pose an unneglectable influence and challenge on the reliable and steady operation of power system. Besides, it will increase the operation complexity of power system, and the multi-link coordination issues will be more and more palpable. It's foreseeable that the proportion of power generation by new energy such as
wind power and photovoltaic in the majority part of China will tend to be high. To address such a challenge, the flexible resources within new energy will be fully mobilized. Therefore, the power system will feature diverse elements, complex operation method and high-dimension planning scheme. Therefore, it's a pressing task to study and develop key technologies on the new energy power system coordination planning.

At present, China's study on new energy power generation consumption is quite limited. Domestic and foreign study in this regard mainly focuses on grid access management and power generation technology. In document [1], according to China's distributed photovoltaic grid access and scheduling management, the advice was proposed on the establishment of new energy power generation consumption capacity evaluation mechanism. In document [2], the study and analysis on key technologies of wind turbine generator and wind farm were performed, and the advice proposed on consolidating wind power generation technology innovation and application;

The existing domestic power system peak regulation focuses on hydropower and coal-fired generator. In document [3], to enhance the willingness for coal-fired generator peak regulation, the coal-fired generator peak regulation compensation calculation method was put forward. In document [4], the coal-fired power peak regulation load distribution model was proposed. By using MFO as the model solving algorithm, the author further cut the total cost of system peak regulation. The coal-fired power generation takes an overwhelmingly dominant role in China's power generation. The regulation capacity is restricted by the generation operation. Therefore, further study needs to be performed on how to give full play to the regulatory role of China's high-proportion coal-fired power;

The main power system production simulation methods include power supply equilibrium, random production simulation and Monte Carlo simulation, etc. There are plenty of studies on power generation portfolio and economic scheduling. Document [5,6] provides multiple methods on the power supply optimal supply. However, this method cannot take into account of load characteristics and power compensation influence. The random production simulation calculation method has been widely applied because of high calculation efficiency and flexibility to address issues. In document [7], the sequence operation theory was used to calculate the system reliability and economics indicator during the balance of supply and demand, therefore obtaining the sequence simulation results. However, it is difficult to control the error of this kind of method. Monte Carlo method is relatively simple. In document [8], the Monte Carlo method is proposed to conduct renewable energy power system production method. This method quite conforms to the actual engineering situation. Due to calculation and sampling times discrepancy, this method cannot meet the production simulation requirements for complex big power system with multiple restraints and multiple power generation types.

Based on the above demands and according to the province's grid actual condition, the author conducts study on the key technology of new energy power system coordination planning. The author also forms the new energy power system coordination simulation method and model to provide technical support for continuously enhancing grid planning level. The study on multiple types of energy operation modeling methods, including new energy power generation, was performed to ultimately realize the coordination simulation of wind, photovoltaic, water, fire and gas power generation.

2. New Energy Power System Coordination Simulation Model and Method

2.1. Modeling process
The time series load curve-based power system is used to determine the operation mode. It's a scheduling simulation model with the focus on daily operation. The modeling process is shown below:
First, according to the installation schedule, consider the unit operation commencement, decommissioning, remodeling, etc. and determine the unit to be put in operation. According to the maintenance schedule, remove the maintenance unit and ultimately determine the operable unit and parameters.

Arrange the unit for output, including the external protocol power transmission, nuclear power set, and then determine the output unit. According to the power area, correct the corresponding load curve.

According to the new energy simulation output randomly generated from the new energy simulation module, arrange new energy output and correct the corresponding load curve.

Based on the corrected multi-area load curve, shed peak and fill in valley for pumping water for energy storage and conventional hydropower unit. Arrange flat or full water pumping and satisfy unit capacity and power supply restrictions. According to the power area, double correct the corresponding load curve.

Optimize remaining unit simulation. Except for the aforesaid calculation results, parameters below should be prepared: artificial designated unit status, positive and negative reserve in each time period, unit time-based quotation or cost, unit startup/stop fees, grid restrictions, etc.

2.2. Model description

2.2.1. Target function
To adapt to different scheduling modes, the target function may be: power market scheduling (minimum system power generation cost), energy-intensive power generation scheduling or open, fair and just scheduling. Take the power market scheduling as an example, the target function may be expressed as:
\[
\min C_c = \sum_{t} \left( C_c(P_t) + C_f(P_t') + C_h(P_t') + C_p(P_t') + C_w(P_t') \right) + \theta C'_c + \eta C'_f
\]

Where: \( T \) denotes time intervals within the optimization cycle; \( C_c(P_t) \) operation cost of generator in case of \( P_t \) output power at \( t \) time interval, subscripts \( c, f, h, p, w \) respectively daytime non-stoppable, stoppable fire power, water power, pumping and new energy; \( C_c \) cut out energy cost; \( P_t \) output power at \( t \) interval; \( D_t \) cut load power at \( t \) interval; \( \theta, \eta, \gamma \) weighted coefficient, usually 1, and subject to adjustment. It shows that the target function represents the scheduling decision after a comprehensive consideration of system power generation economics, cut load cost and cut out new energy.

2.2.2. Restriction condition
(1) Load and power generation balance

\[
[1] P_t + [1] P_t' + [1] P_t'' + [1] P_t''' + [1] D_t = [0] D_t \quad \forall t \in T
\]

(2) Technology output restriction of coal-fired power generator

The technical output restrictions of coal-fired generator mainly include: coal-fired generator output upper/lower limit and climbing constraint.

\[
\begin{align*}
& P_{c_{\text{min}}} I_{c} \leq P_{c}' \leq P_{c_{\text{max}}} I_{c} \\
& P_{f_{\text{min}}} I_{f} \leq P_{f}' \leq P_{f_{\text{max}}} I_{f} \\
& -\Delta P_{c_{\text{down}}} \leq P_{c}' - P_{c} \leq \Delta P_{c_{\text{up}}} \\
& -\Delta P_{f_{\text{down}}} \leq P_{f}' - P_{f} \leq \Delta P_{f_{\text{up}}} \\
& P_{c}', P_{f}', I_{c}, I_{f} \geq 0 \\
& \forall t \in T
\end{align*}
\]

Where: \( P_{c_{\text{min}}}, P_{c_{\text{max}}}, P_{f_{\text{min}}}, P_{f_{\text{max}}} \) denote minimum output and maximum output of unit; \( I_c \) means daytime non-stoppable unit status variable, \( I_{f} \) refers to daytime stoppable unit status variable at \( t \) time interval; \( \Delta P_{c_{\text{down}}}, \Delta P_{f_{\text{down}}} \) and \( \Delta P_{c_{\text{up}}}, \Delta P_{f_{\text{up}}} \) are respectively unit climbing down, climbing up speed.

(3) New energy output restriction

The difference between new energy and conventional energy lies in the changeable and uncontrollable output. During scheduling, control the output within the scope of prediction value or below only based on the daytime prediction value. According to the grid energy conservation and environment preservation, the new energy should better be connected to the grid in full load. The new energy modeling herein introduces the new energy output prediction variable \( P_{w_{\text{ft}}} \), and the daily operation simulation model introduces cut out simulation model. In this manner, the model may cut out a part of new energy output when the system cannot provide peak regulation capacity, system backup capacity is not adequate or new energy output is blocked.

\[
\begin{align*}
P_{w} + P_{w_{\text{ed}}} &= P_{w_{\text{st}}} \\
0 &\leq P_{w}, 0 \leq P_{w_{\text{ed}}} \\
\forall t &\in T
\end{align*}
\]
Where: $P'_t$ denotes new energy output at t time interval; $P'_w$ means cut new energy power at t time interval; $P'_f$ refers to new energy prediction output value at t time interval.

(4) New energy power rejection rate restriction

$$\sum_t P'_w / \Sigma_t P'_f \leq r_{wd}$$

$r_{wd}$ denotes new energy new power rejection rate upper limit ratio, $\Sigma_t P'_w$ stands for cut new energy power sum, and $\Sigma_t P'_f$ is new energy output combination.

(5) Hydropower and pumping output restriction

The hydropower unit optimizes the modeling output at each time interval according to the hydropower unit output scope and daily power generation given by the medium- and long-term cross-domain cascading hydropower optimization scheduling. The daily water pumping volume and power generation balance of the pumping unit should be considered.

$$P_{h \min} \leq P'_h \leq P_{h \max}$$

$$\sum_{i=1}^{T} P'_h \leq Q_{\text{hydro}}$$

$$-P_{p, \text{pump}} I_{p, \text{pump}} \leq P'_p \leq I_{p, \text{gen}} P_{p, \text{gen}}$$

$$I_{p, \text{pump}} + I_{p, \text{gen}} = 1$$

$$\sum_{i=1}^{T} I_{p, \text{gen}} P'_h = \lambda_p \sum_{i=1}^{T} I_{p, \text{pump}} P'_h$$

Where: $P_{h \min}, P_{h \max}$ denotes minimum output and maximum output of hydropower unit, the first line hydropower unit output upper/lower limit restriction. Qhydro means daily power generation, the second line daily power generation restriction. If the optimization result equation is untenable, it means hydropower water rejection, water rejection conversion power generation (hydro) $\sum_{i=1}^{T} P'_h$. $P_{p, \text{pump}}, P_{p, \text{gen}}$ are maximum water pumping volume and power generation at the unit time, the third line pumping unit output upper and lower limit restriction. $I_{p, \text{pump}}, I_{p, \text{gen}}$ are water pumping or power generation status variable at t time interval, the fourth line pumping unit water pumping and power generation mutually exclusiveness. $\lambda_p$ means pumping unit efficiency, the fifth line daily pumping water volume and power generation balance restriction.

(6) System positive/negative backup requirement

$$[1]^{T} D' + r'_u [1]^{T} D'' + [1]^{T} P'_{f, \text{sun}} I_ x + [1]^{T} P'_{f, \text{sun}} I_ y + [1]^{T} P'_{f, \text{sun}} I_ z + [1]^{T} D'_s$$

$$\forall t \in T$$

Where: $ru$ denotes required positive backup rate at time interval t. It should be noted in the formula, the new energy contribution for system backup should be calculated based on the prediction output Pwft. The part, even cut out, should be credited into the backup volume.

$$[1]^{T} P'_{f, \text{sun}} I_ x + [1]^{T} P'_{f, \text{sun}} I_ y + [1]^{T} P'_{f, \text{sun}} I_ z + [1]^{T} D'_s$$

$$\forall t \in T$$

Where: $rt$ denotes required negative backup rate at time interval t. The new energy output should not be credited. It should be deemed that the new energy minimum output is 0, to be cut out any time.

(7) Area backup restriction
Reserve adequate backup capacity for the area load. The area backup restriction may be expressed as:

\[
\begin{align*}
\sum_{c,f,h,p,w,z} (P_{c,max} I_c + P_{f,max} I_f + P_{h,max} + P_{p,gen} + P_{w,uf}) \\
+ \sum_{l,z} f^i_l - \sum_{l,z} f^i_l + D^i_d \geq (1 + r^i_u) D^i_d \\
\sum_{c,f,h,p,z} (P_{c,min} I_c + P_{f,min} I_f + P_{h,min} - P_{p,pump}) \\
+ \sum_{l,z} f^i_l - \sum_{l,z} f^i_l + D^i_d \leq (1 - r^i_d) D^i_d \\
\forall z \in Z, \forall t \in T
\end{align*}
\]

Where: \( Z \) denotes area total number. \( D_z t, \) area \( z \) load at time interval \( t. \) \( ruz t, \) \( rdz t \) respectively positive reserve rate and negative reserve rate of area \( z \) at time interval \( t. \) \( Z + \) and \( Z - \) respectively in and out liaison line at area \( z. \) \( f^i_l \) trend of \( l \) line. The first line of restriction, area positive reserve restriction, the second line area negative reserve restriction.

(8) Grid restriction

Based on the direct current trend model, the line and fracture transmission restriction is established, as shown below:

\[
\begin{align*}
F^i_l = W \cdot A_{ngp} P^i_e \cdot W \cdot A_{ngf} P^i_f + W \cdot A_{ngp} P^i_h + W \cdot A_{ngp} P^i_p + W \cdot A_{ngp} P^i_p' \\
+ W \cdot A_{ngp} P^i' + W \cdot D^i_d - W \cdot D' \\
- f_{l,max} \leq f^i_l \leq f_{l,max} \\
F^i_l = A_{l} \cdot W \cdot A_{ngp} P^i_e + A_{l} \cdot W \cdot A_{ngf} P^i_f + A_{l} \cdot W \cdot A_{ngp} P^i_h + \\
A_{l} \cdot W \cdot A_{ngp} P^i_p + A_{l} \cdot W \cdot D^i_d - A_{l} \cdot W \cdot D' \\
- f_{l,max} \leq f'^i_l \leq f_{l,max} \\
\forall t \in T
\end{align*}
\]

Where: \( F^i_l, F'^i_l \) respectively line and fracture trend matrix at time interval \( t. \) \( W \) generator transfer distribution factor. \( Angc, Angf, Angh, Angp, Angw \) respectively node-unit correlation matrix of different types of units. \( Asl \) fracture-line correlation matrix.

(9) Cross-area power supply restriction

To simulate the specific power supply plan during grid operation, the cross-area power supply restriction is introduced, namely restricting the fracture transmission trend at each time interval.

\[
f^i_l \leq \sum_{l \in S} f^i_l \leq f_{l,max} \quad \forall t \in T
\]

Where, \( S \) denotes line sets included in the cross-regional power supply fracture \( S; \)

(10) Dynamic restriction

Maximum number of startup/stops of coal-fired power within a day. Startup/stop of large-capacity coal-fired generator is not allowed.

3. Case Analysis

3.1. Example data

The example herein: the province’s 220kV and 500kV main grid data, including 2019 yearly 8,760-hour 220kV substation load data, direct/alternate current transmission data, industrial load data, main grid wind farm and photovoltaic station output data.
Main grid line and substation data summary:
- 220kV line: 798 pieces;
- 550kV line: 177 pieces;
- main substations: 117, total capacity 107390MW.

3.2. Example results
(1) Installed capacity: 129 coal-fired generators, total capacity 47615MW; 2 gas-fired generators, total capacity 435MW; 3 hydropower generators, total capacity 868MW; 10 photovoltaic generators, total capacity 3520MW; 50 wind turbine generators, total capacity 6561.4MW.

![Fig 2. Installed capacity](image)

(2) Generator’s annual output results:
- Coal-fired generator power generation 19543911.00MWh, online operation time 4104.46 hours, yearly output ratio 88.88%;
- Gas-fired generator power generation 2095830.00MWh, online operation time 4818 hours, yearly output ratio 0.95%;
- Hydropower generator power generation 3896589.45MWh, online operation time 4104.46 hours, yearly output ratio 1.77%;
- Wind turbine generator power generation 13329774.16MWh, online operation time 2031.54 hours, yearly output ratio 6.06%;
- Photovoltaic generator power generation 5132932.98MWh, online operation time 1458.22 hours, yearly output ratio 2.33%

![Fig 3. The province’s power system 8,760-hour generator output in 2019](image)

(3) Power system operation cost:
The province’s power system yearly operation cost is RMB 16.432 billion.
Table 1. Power system operation cost

| Time Duration/h | Power system operation cost/100 million |
|-----------------|----------------------------------------|
| 2019-01-01 00:00:00 to 2019-12-31 23:00:00 | 164.32 |

(4) New energy consumption

According to the yearly power generation balance of analog output, the province’s wind power rejection volume 26355.87MWh, power rejection rate 0.20%, wind power available duration 2031.54 hours; photovoltaic power rejection rate 17946.82MWh, power rejection rate 0.35%, photovoltaic available duration 1458.22 hours.

Fig 4. Peak down margin and rejection power of wind and photovoltaic

Table 2. Power supply balance (year)

| Load power supply (MWh) | 149645736.11 |
|-------------------------|--------------|
| Outer transmission (MWh)| 70243301.93  |
| Direct current outer transmission power supply (MWh) | 25310274.00 |
| Alternate current outer transmission power supply (MWh) | 44933027.93 |
| System total power generation (MWh) | 219889038.04 |
| Coal-fired generator power generation (MWh) | 195433911.44 |
| Gas-fired generator power generation (MWh) | 2095830.00 |
| Wind turbine generator power generation (MWh) | 13329774.16 |
| Photovoltaic generator power generation (MWh) | 5132932.98 |
| Hydropower generator power generation (MWh) | 3896589.45 |
| Coal-fired generator online operation time (h) | 4104.46 |
| Gas-fired generator online operation time (h) | 4818.00 |
| Hydropower generator online operation time (h) | 4489.16 |
Wind power rejection volume (MWh) | 26355.87
---|---
Wind power rejection rate (%) | 0.20
Wind turbine generator available duration (h) | 2031.54
Photovoltaic power rejection volume (MWh) | 17946.82
Photovoltaic power rejection rate (%) | 0.35
Photovoltaic generator available duration (h) | 1458.22

(5) Grid blockage

Table 3. Line’s yearly maximum availability

| Line   | Begin node | End node | Extreme transmission capacity (MVA) | Voltage rating (kV) | Maximum availability(%) |
|--------|------------|----------|-------------------------------------|---------------------|--------------------------|
| Line-010 | Node-21    | Node-20  | 151.38                              | 230.00              | 69.40                    |
| Line-012 | Node-03    | Node-20  | 151.38                              | 230.00              | 69.40                    |
| Line-011 | Node-21    | Node-20  | 1154.84                             | 525.00              | 62.01                    |
| Line-007 | Node-04    | Node-06  | 2273.32                             | 525.00              | 49.28                    |
| Line-023 | Node-51    | Node-12  | 2964.4                              | 525.00              | 37.50                    |
| Line-104 | Node-51    | Node-12  | 2964.4                              | 525.00              | 36.88                    |
| Line-093 | Node-16    | Node-14  | 1964.15                             | 525.00              | 36.36                    |
| Line-057 | Node-10    | Node-12  | 1935.05                             | 525.00              | 35.51                    |
| Line-082 | Node-07    | Node-09  | 557.72                              | 230.00              | 34.43                    |
| Line-112 | Node-14    | Node-06  | 649.35                              | 230.00              | 33.65                    |

4. Conclusion

The author designed the target function, restriction condition and unit combination model of power system simulation model for massive new energy access to the grid. In line with the new energy output, hydropower generator and unit maintenance plan, the author gets the daily simulation of massive new energy access to the grid and power market scheduling, as well as the generator’s output, price and area exchange power generation in each time interval. The author performed refined analysis of power system operation cost, energy consumption, trend blockage and new energy consumption, which will provide technical support for demonstrating the power supply and grid planning scheme.

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