New Energy and UHVDC Power Absorption Capacity Analysis Method Based on Refined Operation Simulation Technology

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Abstract — In order to comprehensively consider a variety of complex factors such as new energy integration, maximum and minimum load, network security constraints, and analyse the new energy absorption capacity of the power grid before and after the UHVDC power access in the province, and study the steady-state power absorption capacity of UHVDC, this paper deeply studies refined time series operation simulation model, designs constraints before and after the UHVDC power access, and establishes a new energy and UHVDC power absorption capacity analysis method based on refined operation simulation technology, and applies this method to analyse the power grid of the province before and after the UHVDC power is put into operation. This method provides technical support for demonstrating power supply and power grid planning schemes.

1. Introduction
In recent years, the installed scale of new energy in China has continued to expand [1]. For the sample province, it is estimated that by the end of 2020, the installed capacity of wind power in its power grid will reach 3.6 million kilowatts, and the installed capacity of photovoltaic will reach 2.25 million kilowatts, accounting for 12% and 8% of the total installed capacity of unified regulation respectively. The large-scale access of new energy will lead to an increase in the difficulty of system peak shaving, and the unstable grid load caused by extreme conditions will also limit the capacity of new energy absorption for a long time. After the UHVDC power is connected, UHVDC will also have a direct impact on the power flow, power quality, short-circuit calculation, and reliability of the power system of the province. Under the background of large-scale grid connection of new energy generation and UHVDC power planning, it is urgent to carry out research on the capacity of new energy absorption, system peak shaving and UHVDC power steady-state absorption.

At present, many literature have carried out research on power grid operation simulation and new energy absorption capacity. Reference [2] analyzes the factors affecting renewable energy absorption and proposes an optimal dispatch model to promote consumption. Reference [3] analyzes the influencing factors of renewable energy absorption in detail and proposes the concept and evaluation method of the contribution of influencing factors of renewable energy absorption, which can more...
accurately measure the impact of different factors on renewable energy absorption capacity. Reference [4] studies the cross-regional networking capacity and power transmission timing characteristics, it uses timing operation simulation technology to conduct a comprehensive quantitative evaluation of renewable energy waste and system operating costs. Tsinghua University's power grid production and operation simulation software (hereinafter referred to as "GOPT software") uses dispatching and operation simulation methods to conduct power, electricity, peak shaving balance analysis and power grid static security analysis on the power grid, supporting the establishment of detailed modeling of large-scale power systems, which supports multi-objective optimization functions when considering multiple network security constraints [5-6].

In order to comprehensively consider a variety of complex factors such as new energy integration, maximum and minimum load, network security constraints, and analyze the new energy absorption capacity of the power grid before and after the UHVDC power access in the province, study the steady-state power absorption capacity of UHVDC. This paper uses a refined time series operation simulation model, aiming at the design constraints before and after the UHVDC power access, establishes a new energy and UHVDC power absorption capacity analysis method based on refined operation simulation technology, and uses this method to analyze the absorption capacity of the province's power grid before and after UHVDC is put into operation.

2 Model and Method

2.1 Modeling process

This paper uses a refined operation simulation model, and its modeling process is shown in the following figure:

![Fig.1. Process of Daily Simulation Model](image-url)
First of all, according to the installation schedule, determine the operation unit under the consideration of unit commissioning, decommissioning and technical transformation, then exclude the maintenance unit according to the inspection plan, finally, determine the operating unit and its parameters;

Then arrange all units that can determine the output, including foreign agreement power transmission, nuclear power units and units that are considered to have specified output, and correct the corresponding load curve according to the area where the power supply is located;

According to the new energy simulation generated by the new energy operation simulation module, the new energy output is arranged, and the corresponding load curve is corrected;

Based on this modified multi-regional load curve, for storage and conventional hydropower units to arrange their peak shaving and valley filling, pumping can be set to flat pumping or full pumping, and meet the capacity, electricity and other constraints of the unit, according to the area where the power supply is located, the corresponding load curve is corrected again.

Finally, the remaining units are optimized and simulated, in addition to the previous calculation results, the following parameters need to be prepared: the state of the manually specified unit, the positive and negative reserve amount of each time period, time-sharing quotation or cost of the unit, start-stop cost of the start-stop unit, and network constraint.

When analyzing the new energy consumption capacity, UHVDC power consumption capacity and system peak shaving capacity based on the timing operation simulation technology, the target function, boundary conditions and constraint conditions are set, and data such as the new energy output and UHVDC power consumption after the access of UHVDC power are obtained, which provides data support for the analysis of the consumption capacity of the power grid.

2.2 Model description

2.2.1 Objective function
In order to maximize the grid's new energy consumption and UHVDC power steady-state consumption, the objective function is set to the lowest total power generation cost of the system, of which the UHVDC power purchase cost and the new energy power generation cost are the lowest, which can make sure the system preferentially absorb UHVDC and new energy.

\[
\min C_{sys} = \sum_{t \in T} \left( C_c(P_c^t) + C_f(P_f^t) + C_h(P_h^t) + C_p(P_p^t) + C_w(P_w^t) + \theta C_w P_{wd}^t \right) + \gamma_c C_c + \gamma_f C_f + \gamma_d c C(P_{dc})
\]

Where: \( T \) denotes time intervals within the optimization cycle; \( C(P^t) \) denotes operation cost of generator in case of \( P \) output power at \( t \) time interval, subscript \( c, f, h, p, w \) respectively represents daytime non-stoppable, stoppable fire power, water power, pumping and new energy power; \( C_w \) indicates cut out new energy cost; \( P_{wd}^t \) indicates abandon cost of new energy power at \( t \) interval; \( D_i^t \) indicates cut load power at \( t \) interval; \( V_i \) cut load loss at each node; \( C_f, C_c \) unit means fire power unit startup-stop cost; \( \theta, \gamma, \gamma \) are weighted coefficients, default is 1, \( C(P_{dc}) \) denotes UHVDC power purchase cost.

2.2.2 Constraint condition
(1) Load and power generation balance

\[
[1]^T P_c^t + [1]^T P_f^t + [1]^T P_h^t + [1]^T P_p^t + [1]^T P_w^t = [1]^T D^t \forall t \in T
\]

Define system net load as follows:
\[ L_{\text{net}}^t = L^t - L_n^t - P_{\text{wmax}}^t - P_{\text{hmax}}^t - P_{\text{ymax}}^t \forall t \in T \]  
(3)

Where: \( L', L_n', P_{\text{wmax}}', P_{\text{hmax}}' \) respectively represent the at time \( t \): system load, the power of the tie line, the maximum output of new energy (the sum of the predicted output of wind power and photovoltaic), and the maximum power of UHVDC absorption (before UHVDC connection, \( P_{\text{hmax}} = 0 \)). The net load of the system is assumed to be the load under the premise of full absorption of UHVDC and new energy output, this will not be repeated below.

Therefore, the power balance constraint can eventually be reduced to:

\[ P_f^t + P_c^t - (\Delta P_c^t + \Delta P_f^t) = L_{\text{net}}^t \forall t \in T \]  
(4)

Where: \( P_f^t \), \( P_c^t \), \( \Delta P_c^t \), \( \Delta P_f^t \), \( L_{\text{net}}^t \) represent the thermal power output of the system, the output of pumping and storage, the power of abandoning UHVDC, the power of abandoning wind and light, and the net load of the system at time \( t \).  

(2) Coal-fired power generator constraints

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

\[
\begin{align*}
& P_{\text{cmin}}^t l_c < P_c^t < P_{\text{cmax}}^t l_c \\
& P_{fmin}^t I_f < P_f^t < P_{fmax}^t I_f \\
& -\Delta P_c^{\text{down}} < P_c^t - P_c^{t-1} \leq \Delta P_c^{\text{up}} \\
& -\Delta P_f^{\text{down}} < P_f^t - P_f^{t-1} \leq \Delta P_f^{\text{up}} \\
& P_c^t, P_f^t, l_c, I_f \geq 0 \\
& \forall t \in T
\end{align*}
\]  
(5)

Where: \( P_{\text{cmin}}, P_{\text{cmax}}, P_{fmin}, P_{fmax} \) denote minimum output and maximum output of unit; \( l_c \) means daytime non-stoppable unit status variable, \( I_f \) refers to daytime stoppable unit status variable at \( t \) time interval; \( \Delta P_c^{\text{down}}, \Delta P_c^{\text{up}}, \Delta P_f^{\text{down}}, \Delta P_f^{\text{up}} \) respectively are unit climbing down, climbing up speed.

(3) Renewable energy generator constraints

The difference between renewable energy and conventional energy is that its output is random and uncontrollable. In the dispatch operation, control the output within the range of the previous forecast value or below; at the same time, according to the requirements of energy conservation and environmental protection of the power grid operation, the new energy is required to be fully connected to the net when the power grid is able to consume. In this paper, the new energy output predictor \( P_{\text{wd}} \) is introduced in the modeling of new energy, and the new energy removal mechanism is introduced in the daily operation simulation model if the model cannot provide peak shaving capacity, or system backup capacity is insufficient, or the new energy output is blocked.

\[ P_c^t + P_{\text{wd}}^t = P_{vf}^t \]  
\[ 0 < P_{\text{wd}}^t, 0 \leq P_{vf}^t \]  
\( \forall t \in T \)  
(6)

Where: \( P_{\text{wd}} \) denotes new energy output at \( t \) time interval; \( P_{vf} \) means cut new energy power at \( t \) time interval; \( P_c^t \) refers to new energy prediction output value at \( t \) time interval.

(4) Renewable energy abandonment rate constraints

\[ \sum_t P_{\text{wd}}^t / \sum_t P_{vf}^t \leq r_{\text{wd}} \]  
(7)

\( r_{\text{wd}} \) indicates the upper limit ratio of new energy power abandoned, \( \sum_t P_{\text{wd}}^t \) represents the sum of new energy cut power, and \( \sum_t P_{vf}^t \) is sum of new energy output.

(5) Hydropower and storage unit constraints
The output range of hydropower units and the daily power generation capacity given by hydropower units according to the results of medium- and long-term cross-basin cascade hydropower optimization scheduling are optimized and allocated in each period of time; balance of daily pumping and power generation are considered when it comes to the pumping unit.

\[
P_{\text{hmin}} \leq P^t_h \leq P_{\text{hmax}}
\]

\[
\sum_{t=1}^{T} P^t_h \leq Q_{\text{hydro}}
\]

\[
\{-P_{p,\text{pump}} I^t_{p,\text{pump}} \leq P^t_h \leq I^t_{p,\text{gen}} P_{p,\text{gen}}
\]

\[
I^t_{p,\text{pump}} + I^t_{p,\text{gen}} = 1
\]

\[
\sum_{t=1}^{T} I^t_{p,\text{gen}} P^t_h = \lambda_p \sum_{t=1}^{T} I^t_{p,\text{pump}} P^t_h
\]

Where: \( P_{\text{hmin}}, P_{\text{hmax}} \) denotes minimum output and maximum output of hydropower unit, the first line represents the upper and lower limit constraints of the hydropower unit output; \( Q_{\text{hydro}} \) represents daily power generation, the second line indicates daily power generation restriction. If the optimization result equation is untenable, it means that hydropower is abandoned, water rejection conversion power generation \( Q_{\text{hydro}} - \sum_{t=1}^{T} P^t_h \). \( P_{p,\text{pump}}, P_{p,\text{gen}} \) are maximum water pumping volume and power generation at the unit time, the third line indicates indicates the upper and lower limit constraints of the output of the pumping unit, \( I^t_{p,\text{pump}}, I^t_{p,\text{gen}} \) are water pumping or power generation status variable at t time interval, the fourth line indicates the mutually exclusive constraint between the pumping and power generation state of the pumping unit. \( \lambda_p \) means pumping unit efficiency, the fifth line indicates the balance constraint between the daily pumping and power generation of the pumping unit.

(6) System positive and negative reserve constraints

\[
[1]^T D^t + r^t \leq [1]^T P_{\text{cmax}} I_c + [1]^T P_{\text{max}} I_f + [1]^T P_{\text{hmax}} + [1]^T P_{\text{w} f} \forall t \in T
\]

Where: \( r \) 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 \( P_{\text{w} f} \). The part, even cut out, should be credited into the backup volume.

\[
[1]^T P_{\text{cmin}} I_c + [1]^T P_{\text{min}} I_f + [1]^T P_{\text{hmin}} \leq [1]^T D^t - r^t \forall t \in T
\]

Where: \( r^t \) 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) Divisional reserve constraints

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

\[
\sum_{z \in Z} \left( P_{\text{cmax}} I_c + P_{\text{fmax}} I_f + P_{\text{hmax}} + P_{p,\text{gen}} + P_{p,\text{pump}} \right) + \sum_{t=1}^{T} f^t - \sum_{t=1}^{T} f^t + D^t \leq \left(1 - r^z \right) D^t
\]

\[
\sum_{z \in Z} \left( P_{\text{cmin}} I_c + P_{\text{fmin}} I_f + P_{\text{hmin}} - P_{p,\text{pump}} \right) + \sum_{t=1}^{T} f^t - \sum_{t=1}^{T} f^t + D^t \leq \left(1 - r^z \right) D^t
\]

Where: \( Z \) means the number of areas; \( D^t \), area \( z \) load at time interval \( t \), \( r^z \), \( r^z \) respectively represent positive reserve rate and negative reserve rate of area \( z \) at time \( t \). \( r^z \) and \( z \) respectively represent in and
out liaison line at area z, \( f' \) trend of / line. The first line of restriction represents positive reserve restriction, the second line represents negative reserve restriction.

(8) Network constraints

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

\[
\begin{align*}
F_l^t &= WA_{ngc}P_c^t + WA_{ngf}P_f^t + WA_{ngh}P_h^t + WA_{nge}P_p^t + WD^t \\
&\quad -f_{l_{\text{max}}} \leq f_l^t \leq f_{l_{\text{max}}} \\
F_s^t &= A_{sl}WA_{ngc}P_c^t + A_{sl}WA_{ngf}P_f^t + A_{sl}WA_{ngh}P_h^t + A_{sl}WA_{ngp}P_p^t + A_{sl}WA_{ngw}P_w^t - A_{sl}WD^t \\
&\quad -f_{s_{\text{max}}} \leq f_s^t \leq f_{s_{\text{max}}} \\
&\forall t \in T
\end{align*}
\]

Where: \( F_l^t \), \( F_s^t \) respectively line and fracture trend matrix at time interval t. \( W \) generator transfer distribution factor. \( A_{ngc}, A_{ngf}, A_{ngh}, A_{ngp}, A_{ngw} \) respectively node-unit correlation matrix of different types of units. \( A_{sl} \) fracture-line correlation matrix.

(9) Cross-regional power transmission constraints

In order to simulate the specific transmission plan in the actual grid operation, cross-regional transmission constraints are introduced, that is, the transmission flow of each time period of the section is limited.

\[
f_s^t \leq \sum_{t \in \Theta_s} f^t_i \leq \bar{f}_s^t \quad \forall t \in T
\]

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

3. Case Analysis

Using this analysis method, treating the province's 8760 hours of load data in 2020 as input, simulating the operation of the power grid before and after the UHVDC power is connected in 2021, this paper analyzes the new energy absorption capacity of the power grid and studies the UHVDC steady-state power absorption capacity as follows.

3.1 Before the UHVDC connection

Before the UHVDC power is connected, the output of each type of unit is as follows, the trend of unit output is shown in Figure 2.

- The equivalent annual utilization hours of thermal power units are 3901 hours, the utilization rate of thermal power units is 44.53%
- The equivalent annual utilization hours of hydro power units are 2277 hours, the utilization rate is 25.99%
- The wind power abandonment rate is 0.39%, the equivalent annual utilization hours of wind power are 825 hours
- The photovoltaic power abandonment rate is 0%, the equivalent annual utilization hours of photovoltaic are 326 hours
Fig 2. The province’s power system generator output before UHVDC is put into operation

New energy consumption rate is 99.57%. As Figure 3 and 4 shows, the absorption rate of wind power reaches its lowest in February.

Fig 3. Total wind power output curve of the whole province before UHVDC was put into operation
Fig 4. Wind power absorption rate curve of the whole province before UHVDC was put into operation

According to the setting of constraints, the main reason for renewable energy abandonment is that the net load of the system is sometimes smaller than the minimum output of thermal power unit, as shown in the following figure.

Fig 5. System net load and minimum output of thermal power units on February 13

3.2 After the UHVDC connection
After the UHVDC power is connected, the power transmission of UHVDC is maximized, and the output of thermal power and hydropower is further reduced. The output of each type of unit is as follows, the trend of unit output is shown in Figure 6.

- The equivalent annual utilization hours of thermal power units are 2818 hours, the utilization rate is 30.58%
• The equivalent annual utilization hours of hydro power units are 1728 hours, the utilization rate is 18.76% 
• The wind turbine abandoned power is 1905 MWh, the abandoned wind rate is 0.19%, and the equivalent annual utilization hours of wind power are 1119 hours 
• Photovoltaic unit abandoned power is 1222MWh, abandoned rate is 0.58%, the equivalent annual utilization hours is 620 hours.

Fig 6. The province’s power system generator output after UHVDC is put into operation

New energy consumption rate is 99.77%. As Figure 7 and 8 shows, the absorption rate of wind power reaches its lowest in December.

Fig 7. Total wind power output curve of the whole province after UHVDC was put into operation
After UHVDC power is connected, its average absorption rate is 99.54%. The absorption rate curve is shown in the following figure. During the National Day, UHVDC power absorption rate is the lowest.

After the UHVDC was put into operation, the minimum output of the thermal power unit is larger than the system net load for a total of 224 hours in October. UHVDC abandonment occurs in 30 days because of the minimum output of thermal power unit being higher than the system net load. Among them, the operation simulation data on October 1 is shown in the following figure:
In this paper, the objective function, constraint conditions and unit combination model of the power system operation simulation model considering UHVDC power access and large-scale grid connection of new energy are designed, and a variety of complex factors such as new energy integration, maximum and minimum load, and network security constraints are comprehensively considered. The analysis method of the power grid's new energy and UHVDC power absorption capacity based on refined operation simulation technology is established. The author applies this method to analyze the power grid's absorption capacity of new energy and UHVDC before and after the UHVDC power is put into operation in a province. The operation simulation results show that the province's new energy absorption rate before the UHVDC is put into operation is 99.57%, after it is put into operation, this absorption rate is increased to 99.77%, the UHVDC power absorption rate is 99.54%. The overall absorption capacity of the system is strong. The main factor restricting the absorption capacity of new energy and UHVDC power is that under some circumstances, the minimum output of thermal power units is higher than the net load of the system. This analysis result provides technical support for demonstrating the power grid planning scheme.

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