Research on Wind and PV Power Consumption Strategy Considering Limited Flexible Regulation of Transmitted Bundling Power on Tie-Line

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Abstract. There are many “west-to-east” electricity transmission lines in China, some of which transmit bundling power among which including wind and photovoltaic (PV) power. On one hand, according to the interconnected power systems theory, the transmitted power on trans-regional tie-lines needs to keep relatively stable. Therefore, wind turbines and PV facilities have to be bundled with other controllable units, e.g., thermal units. On the other hand, the ratio of wind and PV electricity on tie-lines can be improved by making full use of flexible regulation strategy. With which, the transmitted power can be adjusted along with the day-ahead forecast results of wind energy and solar radiation intensity in some degree. Some work was done on the day-ahead limited flexible regulation. Firstly, the operation rules of the interconnected power systems were introduced, and the principle of how to improve the ratio of wind and PV electricity was explained. Then, considering the consumption and power supply economics of renewable electricity, an optimization model was established and the solving method was proposed. Finally, case studies were conducted. The variations of transmitted power curves under different focuses were analysed. The effectiveness of the proposed regulation strategy was confirmed.

1. Introduction
The cumulative installed capacity of wind turbines and PV of China ranks first in the world, most of which are located in western and northern regions of China [1]. In China’s power system, some of the redundant power was transmitted to the central and eastern regions through long-distance transmission lines, e.g., Hami Zhengzhou UHVDC line. Among the transmitted electricity of tie-lines, there was wind and PV power.

According to the interconnected power system theory and investigations [2-3], the long-distance tie-lines usually are cross-regional and the power they transmitted must maintain at relatively stable levels. To meet this operation requirement, wind turbines and PV facilities were bundled with other controllable units. It’s easy to understand, the rate of wind and solar electricity to the transmitted bundling electricity on tie-lines should be increased as far as possible. In fact, the abandonment of wind and PV power and the improvement of wind and PV ratio attract the focus of engineers and researchers [4].

A lot of research has been carried out on the above problems. Early research mainly focused on the evaluation of maximum integrated capacity of wind turbines and PV under zero abandonment [5].
With the increasing installed capacity of wind and PV, Ref. [6] points out that a certain proportion of abandoned wind and PV power is reasonable. The capacity optimization was done for wind-PV-thermal bundling systems where some abandon of wind and PV electricity was allowed. Ref. [7] makes full use of the complementarity between wind and PV power, and the ratio of wind and PV electricity could be increased by optimizing the capacity of wind turbines and PV. Refs. [8-9] evaluated the effect of energy storage equipment on suppressing the volatility of the wind and PV power, which in fact is to optimize the capacity of the energy storage in power system. In those researches, the default is that the tie line transmits a power of the line rated capacity or a certain fixed power.

In addition, some research has considered the characteristics of the power on tie-lines. Analysis from the perspective of multi-regional economic schedule was done. In Ref. [10], the reserve capacity of multi-area from the viewpoint of economic regulation was researched. The uncertainty and constrain of the power on tie-lines are considered. In Ref. [11], the multi-regional coordination optimization of wind-fire bundling system was studied. In which, the constraints of power balance, upper backup and minimum reserve capacity in each region were considered. What’s more, the maximum active power on the tie-line was also considered. In Ref. [12], the power on the tie-line was optimized while with some constraints. N equivalent units were used to simulate the power on the tie-line. The optimal regulation scheduling is carried out with the minimum cost of thermal units and no abandonment of wind power.

Above all, the result is conservative if not considering the adjustment of the transmission power along with the forecast of wind and PV power. The existing research on flexible regulation of power transmitted on tie-lines is rather incomplete. The operating cost of thermal power units in the bundling power system, the ratio of abandoned wind and PV electricity, the rate of wind and PV electricity to annual total bundled electricity, and the space-time changing characteristics of power transmitted on tie-lines are not considered together. In view of the shortcomings, following work was done. Firstly, interconnected power system operation theory is concisely introduced. The feasibility of flexible regulation of transmission power is analyzed. The important role of wind and PV power consumption in the case of Chinese ‘west to east’ transmission engineering is also analyzed. Then, taking the transmitted power on tie-lines as the decision variation, a multi-objective mixed integer optimization planning model was established. The corresponding solving method was proposed. Finally, variations of the external power curve under different focuses are analyzed through an example system. The effectiveness of the proposed optimization regulation method is demonstrated.

2. Limited Flexible Regulation Principle of the Tie-Line Power

2.1. Interconnected Power System Theory
Interconnected power systems are made up of several independent power systems (called the controlled area) connected by tie-lines or other equipment. The “standard” of interconnection [13] is established. The adjustment of electricity in the controlled area needs to balance the change of its internal load at any time. Even if there is a big disturbance, the controlled area must be solved by itself. The power on tie-lines between the different regions is the same as the power exchange plans. For the safe and economic operation of the power grid, the planning value of transmission power will be kept at a few levels to ensure that the controlled area can be under a safe and optimized operation condition.

The above characteristics of the controlled area and the interconnected power system are consistent with the subsequent internet. That is, all of them have features of interconnection, openness, peering and sharing. As a member of the cluster, the controlled area works together through interconnection to ensure maximum and most efficient use of renewable energy.

2.2. Power Transmitted on Tie-Lines
Figure 1 shows the annual statistical data of the daily transmission power of a DC line. It is not
difficult to find out: (1) The power transmitted per day on trans-regional tie-lines is not always constant, but basically it is a constant value or a two-stage power curve; (2) The two-stage power curve basically begins to increase about 9:00 and later remains stable. It begins to reduce at about 21:00 and remains stable before 9:00 next day; (3) The direction of power transmission is fixed. The power transmitted during the daytime is more than the power transmitted at night, which is obviously determined by the load. For other more complicated changes (which rarely appears), it can be considered that the day-ahead regulation plan is a two-stage power curve, but the necessary adjustments are made when the system is in operation.

![Figure 1. Annual statistics of daily transmission power of a DC line.](image)

It can be seen that the day-ahead power transmitted on tie-lines can be flexibly regulated. That is, for the wind-PV-thermal bundling long-distance transmission system (as shown in figure 1), when the wind speed or/and the solar radiation is strong, the dispatcher should increase the power transmitted on tie-lines. On the contrary, the power transmitted on tie-lines should be suitably reduced. It can reduce the risk of abandonment of wind and PV power when the wind and PV source can be made better use of. It can also increase the ratio of wind and PV power in the power system. (This effect exists on many time scales such as day, week and year). When the day-ahead limited but flexible regulation plan is carried out, how to determine the value of power transmitted on tie-lines will be a multi-objective optimization problem. The difficulty lies in considering the operating cost of bundling thermal power units, the ratio of abandoned wind and PV electricity, the ratio of wind and PV power generation and the loss of load shedding.

3. Optimization Model and Solution Ideas
Wind-PV-thermal complementary power generation is as the research object according to the status quo of power supply in the north of China. The day-ahead scheduling plans of tie-lines are as decision variation. Multi-objective operation optimization research is carried out. It fully considers the effect of operation cost of thermal power units, the ratio of abandoned wind and PV electricity, the ratio of wind and PV power generation and the loss of load shedding.

3.1. Two-layer Optimization Model
The 24 hours are divided into \(N\) time periods by taking the hour or 15 mins as an interval. The day-ahead regulation planning of power transmitted on tie-lines is recorded as \(P, P=\{P_1, P_2, ..., P_N\}\). \(P\) is the optimization object. The value of \(P\) is determined by a two-layer optimization model. The operating cost of the thermal power units is recorded as \(C_{\text{fuel}}\), which can be calculated by formulation (1):
\[ C_{\text{fire}} = \sum_{i=1}^{M} \sum_{t=1}^{N} a_i \cdot P_{\text{fire},i,t}^2 + b_i \cdot P_{\text{fire},i,t} + c_i \]  

Among which, \( M \) denotes that there are in all \( M \) thermal units in the system. \( P_{\text{fire},i,t} \) denotes the active power of the \( i \)th thermal power unit in the system at the \( t \)th time interval, \( a_i, b_i \) and \( c_i \) denote the power generation cost coefficient of the \( i \)th unit.

The ration of abandoned wind and PV electricity in the wind-PV-thermal bundling system next day is recorded as \( R_{\text{rej}} \), which can be calculated by the following formulation:

\[ R_{\text{rej}}(P_{\text{PV}}, P_{\text{wind}}) = \frac{E_1(P_{\text{PV}}, P_{\text{wind}}) - E_2(P_{\text{PV}}, P_{\text{wind}})}{E_1(P_{\text{PV}}, P_{\text{wind}})} \]  

\[ E_1(P_{\text{PV}}, P_{\text{wind}}) = \sum_{t=1}^{N} P_{\text{PV},t} + P_{\text{wind},t} \]  

\[ E_2(P_{\text{PV}}, P_{\text{wind}}) = \sum_{t=1}^{N} P'_{\text{PV},t} + P'_{\text{wind},t} \]  

Among which, \( E_2(P_{\text{PV}}, P_{\text{wind}}) \) denotes the sum of wind and PV power consumption in \( N \) time intervals when the day-ahead regulation planning is \( P \) and the capacity of wind and PV are \( P_{\text{wind}} \) and \( P_{\text{PV}} \). \( E_1(P_{\text{PV}}, P_{\text{wind}}) \) denotes the sum of wind and PV power consumption in \( N \) time intervals with no abandoned wind and PV electricity. \( P_{\text{wind},t} \) and \( P_{\text{PV},t} \) denote the active power wind and PV power generated when installed capacity respectively is \( P_{\text{wind}} \) and \( P_{\text{PV}} \) with no abandonment of wind and PV at the \( t \)th time interval. \( P'_{\text{wind},t} \) and \( P'_{\text{PV},t} \) denotes the consumption of wind and PV active power generation at the \( t \)th time interval.

The ration of wind and PV power generation in the wind-PV-thermal bundling system next day is recorded as \( R_{\text{ren}} \), which can be calculated by the following formulation:

\[ R_{\text{ren}} = \frac{E_2(P_{\text{PV}}, P_{\text{wind}}) - \sum_{t=1}^{M} \sum_{i=1}^{N} P_{\text{fire},i,t}}{E_2(P_{\text{PV}}, P_{\text{wind}})} \]  

\[ E_2(P_{\text{PV}}, P_{\text{wind}}) = \sum_{t=1}^{N} P_{\text{PV},t} + P_{\text{wind},t} \]

Whether there is a feasible solution for the next day’s unit commitment or not is important. It is closely related to the opening and closing status of the unit in the last interval of the previous day. Therefore, the bundling system may exist the risk of not satisfying the \( P \). The unsatisfied part is the unsupplied electricity. The load-cutting risk is \( C_{\text{uns}} \), which is calculated by the following formulation:

\[ C_{\text{uns}} = k_{\text{uns}} \left( \sum_{t=1}^{N} P_{t} - E_2(P_{\text{PV}}, P_{\text{wind}}) - \sum_{i=1}^{M} \sum_{t=1}^{N} P_{\text{fire},i,t} \right) \]  

Among which, \( k_{\text{uns}} \) denotes the penalty factor for the lack of power supply. Ref. [14] has introduced in detail.

Since the physical meanings and dimensions of \( C_{\text{fire}}, R_{\text{rej}}, R_{\text{ren}}, \) and \( C_{\text{uns}} \) are quite different, they need to be standardized by the following formulation:

\[ y_{ob} = k_1 \cdot \frac{C_{\text{fire}}}{C'_{\text{fire}}} + k_2 \cdot \frac{R_{\text{rej}}}{R'_{\text{rej}}} + k_3 \cdot \frac{R_{\text{ren}}}{R'_{\text{ren}}} + k_4 \cdot \frac{C_{\text{uns}}}{C'_{\text{uns}}} \]  

\[ C'_{\text{uns}} = k_{\text{uns}} \cdot \# - \text{ASAI} \cdot \sum_{t=1}^{N} P_{t} \]  

Among which, \( k_1, k_2, k_3 \) and \( k_4 \) denote the weighting coefficient of \( C_{\text{fire}}, R_{\text{rej}}, R_{\text{ren}}, \) and \( C_{\text{uns}}. \) \( C'_{\text{fire}} \) denotes thermal units’ operation cost when the installed capacity of the wind and PV is zero. \( R'_{\text{rej}} \)
denotes the average value of the abandoned wind and PV electricity in China this year. \( R'_{\text{ren}} \) denotes the ration of China’s current wind and PV electricity consumed by the whole society. \( C'_{\text{uns}} \) denotes the average value of users’ power failure loss under the condition of satisfying China’s power supply reliability rate. ASAI denotes the reliability of power supply of China.

The outer optimization model of this paper is as follows:

\[
\begin{align*}
\min \quad & y_{ob} \\
\text{s.t.} \quad & \sum_{j=1}^{N} n_{c_j} \leq n_{c_{\text{max}}} \\
& \sum_{i=1}^{N} P_{i} \geq E_{\text{min}} \\
& \min(P) \geq P_{\text{min}} \\
& \min(P) \leq P_{\text{max}} \\
& \sum_{j=1}^{M} (P_{\text{fire},i,j} - P_{\text{fire},i,j}) \geq P_{\text{res}}
\end{align*}
\]

Among which, \( n_{c_{\text{max}}} \) denotes \( P \)'s upper limit of variable number. \( n_{c_{\text{min}}} \equiv 1 \) when \( P_{t}=P_{t+1} \), or \( n_{c_{\text{min}}}=0 \). \( E_{\text{min}} \) denotes the lower limit of transmission power the next day; \( P_{\text{max}} \) denotes the lower limit of day-ahead regulation planning power. \( P_{\text{max}} \) denotes the upper limit of day-ahead regulation planning power. \( P_{\text{res}} \) denotes the lower limit of rotating backup needing to meet by UHV system at any time. \( P_{\text{fire},i,j} \) denotes rated capacity of \( i \)th thermal unit.

It can be seen from formulations (1) to (6) that computing \( C_{\text{fire}}, R_{\text{rej}}, R_{\text{ren}} \) and \( C_{\text{uns}} \) needs such middle variations as \( P_{\text{fire},i,r}, P_{\text{wind},t} \) and \( P_{\text{PV},t} \). They only can be obtained by day-ahead economic dispatch simulation. The inner layer optimization of this paper is based on the unit commitment of the previous economic regulation simulation. The goal is to minimize the operation cost of the system, whose premise is that system consumes wind and PV power generation as much as possible. The inner layer optimization model is as follows:

\[
\begin{align*}
\min \quad & C_{\text{fire}}(P_{\text{PV}}, P_{\text{wind}}) \\
\text{s.t.} \quad & g(P_{\text{PV}}, P_{\text{wind}}) = 0 \\
& h(P_{\text{PV}}, P_{\text{wind}}) < 0
\end{align*}
\]

Among which, \( g(P_{\text{PV}}, P_{\text{wind}}) \) and \( h(P_{\text{PV}}, P_{\text{wind}}) \) respectively denote equation and inequality constraints for the unit commitment, which is introduced in Ref. [15].

3.2. Model Solution Ideas

The two-layer optimization model in this paper is a mixed integer nonlinear programming problem with inner layer and outer layer optimization intersecting. The solution of this model is complicated.

Firstly, the \( P \) is simplified according to the actual situation. The \( P \) is maintained at a few stable power levels per day in the actual system [4]. A two-stage model is adapted while formulating the day-ahead regulation plan. It is as follows:

\[
P = \left[ \frac{P_{2,1}, \ldots, P_{2,n_{1}}, P_{1, \ldots, P_{1,n_{2}}}, P_{2, \ldots, P_{2,n_{3}}}}{n_{1}, n_{2}, n_{3}} \right]
\]

\[
N = n_{1} + n_{2} + n_{3} \quad \text{(11)}
\]

\( P_{1} \geq P_{2} \)

Formulation (11) means that the power transmitted during the day is not less than the power transmitted at night. In addition, the division of \( n_{1}, n_{2} \) and \( n_{3} \) is actually relatively fixed. \( P \) can be set as
follows according to the investigation results of the actual system. The power transmitted begins to increase around 9:00 and later keep stable. It would reduce at about 21:00 and later continue to keep stable until 9:00 the next day.

Then, according to Ref. [16], the operating cost of thermal power units can be made segment linearization processing. The inner layer optimization model (10) is transformed into a mixed integer linear programming problem, which can be solved by mature commercial software. When the value of \( P \) makes the first unit commitment have no solution, it can continue to try the unit commitment after using the load-cutting strategy in Ref. [13]. The feasible solution of the unit commitment will be found.

Finally, the optimization of \( P_1 \) and \( P_2 \) adopts breadth-first search strategy, which can be divided into the following five steps:

1. Set \( P_1 = P_{\text{min}} \), \( P_2 = P_{\text{min}} \), calculate and save the value of \( C_{\text{fire}} \);
2. Set \( P_1 = P_{\text{min}} + \) and \( P_2 = P_{\text{min}} \), calculate and save the value of \( C_{\text{fire}} \);
3. Set \( P_2 = P_{\text{min}} + \), repeat the calculation and save the value of \( C_{\text{fire}} \) until \( P_2 > P_1 \);
4. Repeat (2) and (3) until \( P_1 = P_{\text{max}} \);
5. Search for the minimum value of all saved \( C_{\text{fire}} \). The scheduling plan this day is \( P = [P_1, P_2] \). The values of \( P_1 \) and \( P_2 \) are as the center. A more detailed search can be performed to obtain the more ideal \( P \). Figure 2 shows the search process of the above steps (1) to (4).

4. Example Analysis

4.1. Calculation Parameters
In view of the construction of wind turbines and PV power in northwest China, the transmission system of UHVDC engineering (tie lines) is selected to carry out research. The rated capacity of UHV DC system is 8000 MW. The maximum transmission power of the day-ahead regulation plan is set to 6400 MW. The minimum transmission power is set to 2560 MW. The line regulation plan adopts a two-stage model. The power from 9:00 to 21:00 is a high power level. Other periods are low power levels. The transmission system is a wind-PV-thermal bundling system. The installed capacity of which is 9600 MW, 5000 MW, 5000 MW. Thermal power units are made up of 6 supercritical units (whose rated capacity is 600MW) and 6 ultra-supercritical units (whose rated capacity is 1000 MW). The specific parameters can be found in Ref. [13].

4.2. Simulation Results
Comparison of evaluation results under different conditions are carried out. The outer layer optimization is carried out. The different day-ahead regulation plans by setting a variety of evaluation conditions can be compared. The three conditions are shown in table 1. The day-ahead regulation curves are shown in figures 3-5. Table 2 shows the power supply results of \( R_{\text{rej}} \) and \( R_{\text{ren}} \) in three conditions.

It can be seen that different weight coefficients have a great influence on the day-ahead regulation plan. Paying excessive attention to the ration of wind and PV power generation will result in a higher ration of abandoned wind and PV electricity. It is a waste of resource. If excessive attention is paid to avoiding abandoning wind and PV electricity, it is likely to greatly increase the output of thermal
units. It doesn’t meet the long-term planning of the energy revolution. Relatively balanced determination of the weight factor of each indicator not only can ensure a certain ration of wind and PV power generation. It can also avoid too much abandoned wind and PV electricity. So, it can achieve comprehensive optimization.

Figure 3. Transmission power curve of Case 1.  
Figure 4. Transmission power curve of Case 2.  
Figure 5. Transmission power curve of Case 3.

Table 1. Evaluation cases.

|     | k1 | k2 | k3 | k4 |
|-----|----|----|----|----|
| Case 1 | 0  | 0  | 0.1| 0.9|
| Case 2 | 0  | 0.1| 0.1| 0.8|
| Case 3 | 0  | 0.1| 0  | 0.9|

Table 2. $R_{rej}$ and $R_{ren}$ in the three conditions.

|     | Case 1 | Case 2 | Case 3 |
|-----|--------|--------|--------|
| $R_{ren}$ | 18.36% | 16.62% | 15.30% |
| $R_{rej}$ | 0.21%  | 0.11%  | 0      |

5. Conclusion

The limited and flexible regulation aiming at the day-ahead regulation plan of the cross-region tie line is necessary. It can effectively increase the consumed ration of the wind and PV electricity. A two-layer optimization model is established in this paper. The outer layer model is multi-objective optimization. The power transmitted on tie-lines is as the decision variable. The inner layer optimization is the optimization of the day-ahead economic regulation in the case of maximizing the consumption of wind and PV power generation. The two-layer optimization model is complicated. The rapid solving solution of the model is proposed based on the research on the actual system.
Finally, through the simulation of the example system, it is found that the limited flexible regulation on the tie-line can significantly improve the ration of wind and PV power consumed. The effectiveness of the strategy was confirmed.

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