Optimization Method of Annual Power Generation and Transmission Maintenance Plan for New Energy Consumption

Bin Xue¹ᵃ, Xiaowei Ma¹, Yunlong Chu¹, Xuanli Lan²ᵇ, Tianyu Zhang², Yang Wang²
¹ Northwest Branch of State Grid Corporation of China, 710000, China; ² Beijing Tsintergy Technology Co., Ltd, Beijing, 100084, China.

ᵃ xueb@nw.sgcc.com.cn, ᵇ lanxl@tsintergy.com

Abstract. Recently, with the rising proportion of new energy installed capacity in China, the problem of new energy consumption in the northwest region is particularly prominent, and the phenomenon of abandoning wind power and solar power is serious. In order to alleviate this situation, this paper proposes an annual maintenance plan optimization method for new energy consumption. Under the premise of considering the new energy output, the goal is to minimize the limited power of new energy generation and the minimum cost of maintenance. Transmission maintenance planning model is mixed integer linear programming model and can be solved by a solver such as CPLEX. The feasibility of the method is verified by a provincial power grid example, which effectively reduces the limited power of new energy generation.

Keywords: New energy consumption; Maintenance Plan; Maintenance willingness cost; mixed integer linear programming.

1. Introduction
In order to reduce emissions and sustainable development, China vigorously develop new energy. However, in the actual operation, the abandonment of wind and solar is serious, improve the ability of new energy consumption is an important consideration of economic operation. Taking the Northwest Power Grid as an example, the new energy installed in Northwest Power Grid accounted for 33.56% of the total installed capacity in 2016, up 21.56% year-on-year. While the annual utilization of grid-wide wind power in The Northwest Grid in 2016 was 1424 hours, with the wind abandonment rate of 33.3%, and the annual utilization of photovoltaic was 1151 hours, with the abandonment rate of 19.8% [1].

The main causes of wind abandonment and solar abandonment include the following three aspects [2]. The first is the rapid growth of new energy installations. In recent years, the annual growth rate of new energy installed capacity reached 72%, the current northwest region of new energy installed capacity and maximum load ratio of 96%, of which, Gansu Province, the new energy installed capacity and the maximum load ratio is as high as 146%. In the slow growth of electricity consumption, serious barriers between provinces, cross-regional delivery of the peer demand is not strong, some provinces and regions of the new energy space has been saturated. The second is lack of a sound inter-provincial
load following market mechanism, poor thermal power generation regulation capabilities, poor hydropower load following capacity, and low accuracy of new energy forecasts cannot be effectively incorporated into the reserve, making the northwest power grid load following capacity unable to meet the demand for new energy consumption [3]. The structure of the Northwest grid is weak. The coupling relationship between AC and DC and new energy generation brings security and stability issues, which limits the main channels for new energy consumption in the Northwest Power Grid.

Maintenance of power generation equipment and transmission lines will directly affect the capacity of new energy consumption. Reference [3] first proposed an integrated maintenance model for power generation and transmission, and reference [4] proposed an integrated maintenance model for power generation and transmission considering the N-1 criterion. Reference [5] proposed a model for generating unit maintenance planning considering large-scale wind power access. The wind power output was estimated through the wind power probability density function, and the unit's load following capacity was reasonably reserved for short-term power generation planning during the decision-making stage of the maintenance plan. Reference [6], the minimum maintenance cost of the system and the minimum amount of abandoned wind were taken as the optimization goals, and a unit maintenance planning model considering large-scale wind power access was proposed.

In this paper, an optimization model for generating and transmitting maintenance plans considering new energy consumption is established. The optimization goals of minimum new energy constraints and minimum maintenance willingness costs are established. The CPLEX software is used to solve the problems and achieve the collaborative optimization of maintenance plans and operation combinations.

2. Maintenance Plan Coordination Mechanism for New Energy Consumption

2.1. Restricted Power of New Energy in Transmission Channels

The cross-regional delivery of new energy will affect the transmission capacity due to the maintenance and shutdown of related lines, and then affect the power transmission space of new energy. In the process of preparing the maintenance plan, it is necessary to estimate the restricted energy of new energy under different maintenance plan modes, as formula (1).

\[ Q_{i}^{\text{lim}} = \sum_{t=1}^{T} \eta_{i,t} \cdot \Delta P_{i,t} \cdot \Delta T, \quad \forall i \]  

Among them, \( Q_{i}^{\text{lim}} \) represents the limited amount of new energy in the section \( i \) of the transmission channel, \( \Delta P_{i,t} \) represents the reduction in the transmission limit of the section \( i \) during the period of line maintenance, \( T \) represents the duration of the maintenance plan, \( \Delta T \) represents the length of each period, and \( \eta_{i,t} \) represent the transmission channel simultaneous rate of new energy operation in the section \( i \). Reasonably arranging the line maintenance plan can effectively reduce the limited level of new energy electricity and optimize the space for new energy consumption corresponding to the maintenance plan. Reasonably arranging the line maintenance plan can effectively reduce the limited level of new energy electricity and optimize the space for new energy consumption corresponding to the maintenance plan.

2.2. Maintenance Willingness

When optimizing the maintenance plan, full consideration should be given to the maintenance willingness of the power generation company or transmission company applying for the initial maintenance plan, and the adjustment amount of the initial maintenance plan is taken as the maintenance willingness cost, which is used as the quantitative basis and control index for the maintenance plan coordination.

Use \( T_0 \) to indicate the willingness to repair time. If you modify the planned maintenance time, the cost of maintenance willingness will be incurred. This paper assumes that the greater the time variation, the greater the willingness cost for maintenance. In order to quantify the impact of the maintenance plan adjustment, this paper designed the maintenance willingness cost function according to the size of the maintenance willingness, as shown in Fig.1.
3. Maintenance Optimization Model

3.1. Optimization Goal
Based on the maintenance plan of transmission equipment, the limited power from new energy is quantitatively analyzed and included in the target function. It also reduces the adjustment of the maintenance plan and quantifies the adjustment of the maintenance time through the maintenance willingness cost parameter, as formula (2).

\[
\min \quad \omega_1 F_1 + \omega_2 F_2
\] (2)

\( F_1 \) indicates the cost of maintenance intention, \( F_2 \) indicates new energy limited power, \( \omega_1 \) and \( \omega_2 \) are the weight of the willingness cost and new energy limited power respectively, \( \omega_1 + \omega_2 = 1, \omega_1 \geq 0, \omega_2 \geq 0 \) and the proportion allocation of \( \omega_1 \) and \( \omega_2 \) is adjusted according to the focus of the maintenance plan.

3.2. Main constraints analysis.
The maintenance optimization model contains the following constraints:

1. Unit output limit constraints
   \[
   P_t \leq P_{i,t} \leq P_{i,\text{max}}
   \] (3)
   In formula, \( P_{i,t} \) represents the unit \( i \) output, during the \( t \), \( P_{i,\text{max}} \) and \( P_{i,\text{min}} \) represent the upper and lower limits of unit \( i \) output, respectively.

2. Node power balance constraints
   \[
   \sum_{j(k,s)} F_{j,t} - \sum_{j(k,s)} F_{j,t} + \sum_{v(i,s)} P_{i,t} = d_{k,t} \forall k, \forall t
   \] (4)
   \( d_{k,t} \) represents the load of the node \( k \) in the t-time period, and \( F_{j,t} \) represents the current of line during period \( t \). \( \forall j(k,s) \) is the set of all lines with \( k \) as the initial node. \( \forall j(i,k) \) is the set of all lines with \( k \) as the termination node, and \( \forall i(k) \) is all the units located at node \( k \).

3. Branch flow constraints
   \[
   |F_{j,t} - (\theta_{a,t} - \theta_{b,t})/x_{ab}| \leq C(1 + \sum_{t=t-MD_{j+1}^{k+1}} Y_{j,t}) \forall j, \forall t
   \] (5)
   \( \theta_{a,t} \) is the voltage phase angle of the starting node \( a \) of the line \( j \) during the period \( t \); \( \theta_{b,t} \) is the voltage phase angle of the ending node \( b \) of the line \( j \) during the period \( t \); \( x_{ab} \) is the branch reactance, and \( C \) is a large constant.

4. Line transmission limit constraints
   \[
   |F_{j,t}| \leq F \sum_{t=t-MD_{j+1}^{k+1}} Y_{j,t}
   \] (6)
   \( F_{j,\text{max}} \) is the transmission limit of the line \( j \).

5. Critical section transmission limit constraints
   \[
   P_{b,t}^- - \Delta P_{b,t}^- \leq \sum_{j=1}^{b} P_{j,t} \leq P_{b,t}^+ - \Delta P_{b,t}^+, \forall b
   \] (7)
   \( I_b \) is the set of lines included in key section \( b \), \( P_{b,t}^+ \) and \( P_{b,t}^- \) are the positive and negative transmission limits of section \( b \) during time period \( t \), \( \Delta P_{b,t}^+ \) and \( \Delta P_{b,t}^- \) are the positive and negative
limited power values for section \( b \) due to the implementation of the line maintenance plan during time period \( t \).

4. Example analysis
This paper uses a Chinese provincial power grid example for analysis and testing and compiles the provincial power grid's 2019 maintenance plan. The provincial grid includes 557 units, 931 buses, 1496 lines, and 25 sections. In the example, there are 555 lines planned for maintenance, 226 units and 50 buses.

Table 1. Main maintenance equipment optimization results and constraints

| Maintenance equipment | Plan start | Plan end | Duration | Start | End | Maintenance window 1 | Maintenance window 2 | Main constraint |
|-----------------------|------------|----------|----------|-------|-----|----------------------|----------------------|-----------------|
| Unit 19               | 298        | 302      | 5        | 298   | 302 | [280,350]            | [150,180]            | Original plan   |
| Unit 85               | 126        | 127      | 2        | 126   | 127 | [150,170]            | [230,273]            | Maintenance window simultaneous lines |
| Unit 146              | 212        | 220      | 9        | 212   | 220 | [199,260]            |                     | -               |
| Unit 190              | 223        | 227      | 5        | 216   | 220 | [195,241]            |                     | -               |
| Unit 235              | 301        | 312      | 12       | 316   | 327 | [281,334]            | [168,204]            | -               |
| Unit 287              | 130        | 139      | 10       | 135   | 144 | [135,160]            |                     | -               |
| Unit 308              | 324        | 330      | 7        | 324   | 330 | [280,330]            | [170,196]            | Original plan   |
| Unit 423              | 314        | 322      | 9        | 330   | 338 | [280,359]            |                     | New energy limit |
| Unit 479              | 336        | 349      | 14       | 336   | 349 | [280,330]            |                     | Original plan   |
| Bus 150               | 129        | 129      | 1        | 135   | 135 | [112,170]            | [331,350]            | Current limit   |
| Bus 295               | 152        | 152      | 1        | 148   | 148 | [89,160]             | [23,66]              | Order           |
| Bus 584               | 76         | 77       | 2        | 76    | 77  | [67,89]              | [98,154]             | Original plan   |
| Bus 741               | 139        | 139      | 1        | 144   | 144 | [98,154]             | [314,348]            | Order           |
| Bus 872               | 145        | 147      | 3        | 145   | 147 | [130,169]            |                     | Original plan   |
| Line 41               | 261        | 268      | 8        | 161   | 168 | [10,56]              |                     | Original plan   |
| Line 85               | 166        | 166      | 1        | 170   | 170 | [89,144]             | [170,196]            | Maintenance window |
| Line 134              | 196        | 199      | 4        | 196   | 199 | [99,230]             |                     | Original plan   |
| Line 200              | 321        | 328      | 8        | 331   | 338 | [300,339]            | [231,250]            | New energy limit |
| Line 230              | 323        | 328      | 6        | 339   | 344 | [314,348]            | [231,250]            | New energy limit |
| Line 299              | 232        | 232      | 1        | 232   | 232 | [221,262]            |                     | New energy limit |
| Line 376              | 292        | 302      | 11       | 292   | 302 | [198,255]            | [287,309]            | -               |
| Line 399              | 159        | 160      | 2        | 168   | 169 | [168,281]            | [10,56]              | Maintenance window |
| Line 580              | 199        | 203      | 5        | 185   | 189 | [181,234]            | [145,189]            | New energy limit |
| Line 723              | 298        | 310      | 13       | 303   | 315 | [281,334]            |                     | -               |
| Line 803              | 155        | 166      | 12       | 155   | 166 | [100,123]            | [145,189]            | New energy limit |
| Line 998              | 232        | 239      | 8        | 232   | 239 | [204,254]            |                     | New energy limit |
Table 1 shows the results of maintenance optimization for some units, buses and lines in the provincial power grid. It can be seen that:

1) Due to the unit 235, line 376 and line 723 belong to a mutually exclusive maintenance set, and the planned maintenance time overlaps, the mutually exclusive maintenance constraints are not met. Moreover, in order to minimize the maintenance willingness cost, the maintenance optimization results of unit 235 and line 723 are [303, 315] and [316, 327], respectively, which is close to the maintenance interval of line 376 [292, 302].

2) Since unit 146 and unit 190 belong to a simultaneous maintenance set, but the planned maintenance intervals are [212, 220] and [223, 227] respectively, the problem of repeated power outages has been avoided after optimization.

Table 2 shows the results of new energy limitation. It can be seen that:

1) Unit 146 and unit 190 belong to section 5, and the simultaneous maintenance of the two units did not cause the section transmission capacity to decrease, so it did not cause the new energy capacity to be limited.

2) Unit 423, line 200 and line 230 belong to section 8. As the unit 423 and line 230 or line 200 and line 230 are overhauled at the same time, the limit transmission capacity of the section will be reduced, and new energy consumption will be limited, the solution is to arrange the unit 423 and the line 200 simultaneously.

3) Simultaneous maintenance of line 580 and line 998 will cause 700MW of new energy to be restricted. Therefore, the optimized maintenance result is that line 580 is arranged according to the original plan, and line 998 is separated from it.

5. Conclusion
This paper proposes an optimization model for power generation and transmission maintenance plans for new energy consumption. By taking into account the simultaneous rate of new energy output, the minimum amount of new energy is considered as one of the optimization goals, and the minimum cost of maintenance is considered, so that the maintenance plan obtained can be well coordinated, and economic feasibility and new energy consumption can be taken into account.

References
[1] Y.B. Shu, Z.G. Zhang, J.B. Guo, Z.L. Zhang. The Analysis of Key Factors and Solutions for New Energy Elimination. [J]. Proceedings of CSEE, 2017, 37 (01): 1-9.
[2] Z.Y. Liu, Q.P. Zhang, C. Dong, L. Zhang, Z.D. Wang. Through Ultra-high Voltage DC to Achieve Large-scale Energy Base Wind, Photovoltaic, Thermal Power High-efficiency Safe Delivery Research. [J]. Proceedings of CSEE, 2014, 34 (16): 2513-2522.
[3] C. Fang, Q. Xia, X. Sun. Consider the Overhaul Plan of Large-scale Wind Power Generators. [J].
Automation of Electric Power Systems, 2010, 34 (19): 20-24+74.

[4] R. Billinton and F. A. El-Sheikhi, "Preventive maintenance scheduling in power generation systems using a quantitative risk criterion," in Canadian Electrical Engineering Journal, vol. 8, no. 1, pp. 28-39, Jan. 1983.

[5] C. Fang. Research on Theories and Methods of Interactive Maintenance Scheduling [For the Degree Doctor of Engineering], Beijing: Tsinghua University Electrical Engineering School, 2010.

[6] Y. Wang, H. Zhong, Q. Xia, D. S. Kirschen and C. Kang, "An Approach for Integrated Generation and Transmission Maintenance Scheduling Considering N-1 Contingencies," in IEEE Transactions on Power Systems, vol. 31, no. 3, pp. 2225-2233, May 2016.