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A Novel Transmission Network Planning Framework under the New Power System

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Abstract. With the continuous development and construction of the new power system, there would be a large number of renewable energy connected to the electric network in the future. And the uncertainty of renewable energy would have a greater impact on the power grid, such as excessively large investment and low utilization rate. In view of this, this paper fully considers the adjustable comprehensive resources of the power supply and the load side, and proposes a novel transmission network planning framework under the new power system. Further, from the aspects of economy and reliability, an evaluation system of novel transmission network planning framework is established. At last, taking a municipal 220 KV power grid as an example, the novel transmission network planning framework is applied, and the effectiveness of the proposed planning framework is verified.

1. Introduction

With the rapid development of the new power system, a high proportion of renewable energy on the grid would become a fundamental feature of the future power system[1]. However, the randomness and uncertainty of renewable energy such as wind and photovoltaic power have a profound impact on the planning of power system[2]. The traditional grid planning method is based on the annual maximum load and does not consider the grid connection of renewable energy and other resources, possibly resulting in large investment and low utilization rate. Therefore, there is an urgent need for a better planning framework to meet the new needs of network planning under the development of the new power system.
In recent years, there has been a growing interest in the novel transmission network planning. The literature [3,4] analysed the uncertainties in the new power system, and used robust theory for optimization modelling. The literature [5,6] demonstrated the impact of high percentage of renewable energy connected to the network, and provided an outlook on transmission network planning. The literature [7,8] considered the uncertainty of renewable energy and the characteristic of bidirectional power flow of battery energy storage system, and a transmission grid planning approach included energy storage was proposed. The literature [9,10] constructed a transmission network planning model considered demand response, which analysed the influence of demand response resources on the network. In summary, the existing studies are limited to consider the impact of a single adjustable resource on transmission network planning, while few studies have combined renewable energy, energy storage and demand response resources as adjustable comprehensive resources into the novel transmission grid planning.
Therefore, this paper fully considers the need of transmission network planning mode change under the development of adjustable comprehensive resources. Meanwhile, a novel transmission grid planning framework is established, which focuses on two key methods in novel transmission grid planning, including confidence capacity evaluation of renewable energy and load forecasting. Further, an evaluation system of novel transmission network planning framework is constructed. Finally, the effectiveness and feasibility of the proposed planning framework are evidenced through example analysis.

2. A novel transmission network planning framework considering adjustable comprehensive resources

2.1 Demand analysis of transmission network planning improvement under new power system

Under the construction of new power system, the planning of the transmission grid is significantly impacted by the rapid growth of renewable energy, energy storage, demand response resources and other comprehensive resources, in particular: (1) The renewable energy resources connected to network leads to enhanced random fluctuations in tide and increased planning targets, so that network planning probably increase reliability investment while considering environmental protection requirements;

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(2) The application of energy storage transforms some renewable energy with random output into relatively stable adjustable power supply, which can reduce the investment in reliability of power grid, but also makes the power boundary of power grid planning change from static to dynamic interval; (3) The introduction of demand response can improve the optimal allocation of resources, and decrease the investment of the network because it can effectively reduce the peak load and compensate for the fluctuation of renewable energy output.

Traditional power planning is based on the current and planned conventional power supply scale and annual maximum load, carrying out the power balance and the substation capacity demand calculation of the planning year. However, it is simple to cause the problem of high investment and poor utilization rate of the grid. Because the supply side only considers the traditional power supply without taking into account the renewable energy output during planning, and the role of demand-side resources is not considered during load forecasting. Therefore, the impact of adjustable resources on power network planning is analyzed to improve: (1) In terms of planning ideas, the impact of adjustable comprehensive resources on the power system is fully considered; (2) In terms of planning process, a new planning mechanism is explored to form a planning process that fully considers market factors; (3) In terms of planning methods, considering economy and reliability, the transmission network planning theory and method for adjustable comprehensive resources are proposed.

2.2 A novel transmission network planning guidelines considering adjustable comprehensive resources

To build a novel transmission network planning model considering adjustable comprehensive resources, the basic goal should be to construct the new power system and adapt to economic and social development. Reasonable arrangements for the construction of power grids at all levels and promote the optimization of grid structure, in order to achieve reliable power supply and efficient economic operation of the power grid.. Specific ideas are as follows.

2.2.1 Consider the characteristics and impacts of adjustable comprehensive resources

Given that the combination of "renewable energy + energy storage" can provide relatively stable power supply, it should be included in the consideration of regional electric power and energy balance. Likewise, the renewable energy and energy storage should be included in the transmission grid planning as conventional generating sets using confidence capacity evaluation. In addition, load forecasting is carried out for demand response resources in adjustable comprehensive resources, and the results are used as a reference for transmission network planning.

2.2.2 Select the reasonable time sections to carry out safety checks

Considering the fluctuation and uncertainty of renewable energy power, the node with the worst power stability and the lowest power is selected as the time sections to carry out the network security verification according to its power curve. For example, summer peak load and renewable energy full output, summer peak load and renewable energy zero output, winter trough load and renewable energy full output, winter trough load and renewable energy zero output and other extreme conditions.

2.2.3 Demand response cost should be considered in the economic evaluation of transmission network planning scheme

Considering that the introduction of demand response resources into grid planning affects participant costs and system costs, the cost of demand response should be taken into account in the economic evaluation of transmission grid planning framework. In order to more reliably measure the effectiveness and economy of the new planning model.

3. Key methods for the novel transmission network planning considering adjustable comprehensive resources

3.1 Confidence Capacity Evaluation of Renewable Energy

Confidence capacity of renewable energy refers to the capacity of conventional generating sets that can be replaced by renewable energy generators under the premise of equal reliability. It can make the intermittent wind and photovoltaic power and conventional generating sets installed capacity at the same level to compare. In this paper, the equivalent capacity of conventional unit is used to assess the confidence capacity of the wind-PV-ES hybrid power system, that is, the unit with random outage rate is used to replace the renewable energy. When the reliability of replaced system is equal to the system with renewable energy, the capacity of replaced unit with random outage rate is the equivalent capacity of conventional unit.

Considering the complementary benefits between wind, photovoltaic and energy storage, under the new grid planning framework, the wind power, photovoltaic power and energy storage connected to each 220KV electric substation are regarded as a wind-PV-ES hybrid power system. The confidence capacity is defined as the size of the capacity of conventional unit that the wind-PV hybrid power system can be equivalent to under the same reliability. When the confidence capacity is defined under the same reliability, the capacity of wind-PV hybrid power system can be equivalent to the conventional unit. The calculation method is as follows.

Assuming that the output power of the wind-PV-ES hybrid power system is P_h.

$$P_h = P_W + P_{PV} + X_{dc} \tag{1}$$

Where P_W, P_{PV} and X_{dc} are the output power of wind turbine, photovoltaic generator set and energy storage plant respectively. If equation (2) is satisfied, the confidence capacity of the wind-PV-ES hybrid power system C_{un} is considered to be equal to the installed capacity of the equivalent unit, C_{na}.

$$f\left\{C_r, C_W, C_{PV}\right\} = f\left\{C_r, C_{na}\right\} \tag{2}$$

$f\left\{C_r, C_W, C_{PV}\right\}$ indicates the reliability of the system with a conventional unit capacity of C_r, a wind power capacity of C_W and a photovoltaic power capacity of C_{PV}. And $f\left\{C_r, C_{na}\right\}$ indicates the reliability of the system when the capacity of the conventional unit C_r is equivalent to the installed capacity of the unit C_{na}. At this point, the capacity reliability of the wind-PV hybrid power system can be defined as

$$\lambda = \frac{C_{na}}{C_{PV} + C_W} \tag{3}$$

In terms of system reliability metrics, this paper uses the expected energy not served (EENS) as a reference indicator. The expected energy not served (EENS) of the system varies depending on the load P_L and unit status as follows.

$$f_{EENS} = \begin{cases} P_L - \int_{P_{h\min}}^{P_{h\max}} P_h \cdot f_{P_h}(P_h) dP_h, P_L > P_{h\max} \\ \int_{P_{h\min}}^{P_L} (P_L - P_h) \cdot f_{P_h}(P_h) dP_h, P_{h\min} \le P_L < P_{h\max} \end{cases} \tag{4}$$

Where $P_{h\max}$ and $P_{h\min}$ represent the maximum and minimum values of power generation of wind-PV-ES hybrid power system.

3.2 Load forecasting correction considering demand-side resources

Incorporating demand response resources into power grid planning is conducive to improving the optimal allocation ability of resources and reducing system costs. Based on the traditional load forecasting, this paper proposes a correction model of load forecasting considering the load reduction effect of demand-side resources to realize regional maximum load forecasting considering demand-side resources.

The regional maximum load forecast considering demand side resources is

$$P_{DR}^0 = \left(1 - \xi\right) \cdot \gamma \cdot P_{nor}^0 \tag{5}$$

$$\xi = P_d / P_{nor}^0 \tag{6}$$

Where: P_{DR}^0 represents the maximum load forecast considering demand-side resources, MW; ξ represents the demand response rate, %; γ represents the load simultaneous rate, %; P_{nor}^0 represents the maximum load forecast without considering demand-side resources, MW; P_d represents the demand response load forecast, MW.

In summary, through the change of the maximum load before and after considering the demand-side resources, the substation capacity that can be avoided or delayed to construct can be calculated, as shown in the following formula.

$$\Delta C = R\left(P_{nor}^0 - P_{DR}^0\right) \tag{7}$$

Where: ΔC indicates the substation capacity that can be avoided or delayed after considering demand-side resources, MVA; R indicates the capacity-load ratio.

4. Evaluation of novel transmission network planning based on adjustable comprehensive resources

4.1 Reliability evaluation of novel transmission network planning based on adjustable comprehensive resources

The reliability evaluation of transmission grid is mainly used to evaluate the reliability of power supply, including two aspects: security and reliability evaluation of power supply. For power supply security evaluation, the novel transmission network planning framework takes into account the uncertainty of renewable energy output, mainly selects the extreme conditions for security verification. Through the power flow calculation, short-circuit current calculation and “N-1” security check of the planned grid, the security and stability analysis are carried out. For the reliability evaluation of grid, the target grid is evaluated by setting reliability evaluation indexes of power supply. For instance, insufficient load of system, insufficient energy of system, average interruption frequency of system, average interruption duration of system, average reliability of power supply of system, and average unavailability of power supply of system.

4.2 Economic evaluation of novel transmission network planning based on adjustable comprehensive resources

The economic evaluation is mainly based on two aspects: investment cost of construction and whole life cycle cost. Among them, the investment cost of construction aspect is mainly selected the increase power supply of unit investment and increase load of the unit investment as the main indicators to measure the economy of the scheme; The whole life cycle cost aspect mainly considers the total life cycle cost including the construction investment, operation and maintenance cost, and the call cost of adjustable comprehensive resources.

The economic evaluation of the construction investment dimension mainly selects two indicators, including incremental power supply of unit investment and incremental load supply of unit investment, which are calculated as follows.

$$IS_{UI} = (S - S_0)/C_C \tag{8}$$

$$IL_{\mathrm{UI}} = (L - L_0)/C_C \tag{9}$$

Where IS_{UI} and IL_{UI} are the incremental power supply of planned unit investment and the incremental load of planned unit investment, respectively; S and L are the power supply of planned end-of-period and the maximum load of planned end-of-period; S_0 and L_0 are the power supply of end-of-period of the previous plan and the maximum load of end-of-period of the previous plan; C_C is the construction investment.

The whole life cycle cost needs to consider the construction cost, the grid operation and maintenance cost, and the call cost of adjustable comprehensive resources, etc., calculated as follows.

$$C = C_C + C_O + C_L + C_D - C_R \tag{10}$$

Where: C_C indicates the project construction investment, including the investment of line and equipment, C_O indicates the operation and maintenance cost, C_L indicates the network loss cost, C_D indicates the demand response cost, and C_R indicates the depreciated residual value of fixed assets at the end of the operation. Each cost is calculated as follows.

4.2.1 Project construction investment

Project construction investment C_C includes investment in line construction C_{line}, and investment in equipment C_{equ}, which is related to public network construction works, as indicated below.

$$C_C = C_{line} + C_{equ} \tag{11}$$

4.2.2 Operation and maintenance cost

The operation and maintenance cost consider the line and main transformer.

$$C_O = \sum_n^N (1+i)^n R_O \bullet A \tag{12}$$

Where: A is the total fixed assets for the year, including the line and main transformer; N is the length of the operating period, and i is the annual interest rate.

4.2.3 Network loss cost

Network loss cost C_L includes line loss cost C_{L-line} and the loss cost of main transformer C_{L-equ}.

① Line loss cost

$$C_{L-line} = \sum_n^N (1+i)^n N_L \cdot \tau \cdot \Delta P_{\max} \cdot P_{flat} \tag{13}$$

$$\Delta P_{\max} = 3I_L^2 \cdot R = \left(\frac{L_{\max}}{N_L \cdot U \cdot \cos\varphi}\right)^2 \cdot L_L \cdot R_L \tag{14}$$

Where: $\Delta P_{\max}$ is the line loss at maximum load; N_L is the number of lines in the year; I_L is the current value on a single line; $L_{\max}$ is the maximum load in the year.

② Main transformer loss cost

$$C_{L-equ} = \sum_n^N (1+i)^n N_T \cdot \left[\Delta P_0 \cdot T + \Delta P\left(\frac{L_{\max}}{N_T \cdot S \cdot \cos\varphi}\right)^2 \cdot \tau\right] \cdot P_{flat} \tag{15}$$

Where: N_T is the number of main transformers for the year; T is the transformer operating time, assuming T =8760 h.

4.2.4 Adjustable comprehensive resources utilization cost

Demand response costs C_D include load transfer cost C_{D-S} and load shedding cost C_{D-C}.

$$C_D = C_{D-S,fix} + C_{D-S,price} \tag{16}$$

①Load transfer cost

Load transfer cost C_{D-S} includes fixed investment costs $C_{D-S,fix}$ and reduction of electricity revenue caused by the transfer of load $C_{D-S,price}$.

$$C_{\mathrm{D\text{-}S}} = C_{\mathrm{D\text{-}S,\ fix}} + C_{\mathrm{D\text{-}S,price}} \tag{17}$$

$$C_{\mathrm{D\text{-}S,price}} = \sum_n^N (1+i)^n L'_{\max} \cdot R_{\mathrm{D\text{-}S}} \cdot T_{\mathrm{D\text{-}S}} \cdot (P_{\mathrm{peak}} - P_{\mathrm{valley}}) \tag{18}$$

Where: $L'_{\max}$ is the maximum load forecast for the year.

②Load reduction cost

The load reduction cost $C_{\mathrm{D\text{-}C}}$ is the load-shedding compensation cost.

$$C_{\mathrm{D\text{-}C}} = \sum_n^N (1+i)^n L'_{\max} \cdot R_{\mathrm{D\text{-}C}} \cdot P_{\mathrm{D\text{-}C}} \tag{19}$$

4.2.5 Depreciable residual value of fixed assets

$$C_{\mathrm{LR}} = R_{\mathrm{LR}} \cdot C_{\mathrm{line}} \tag{20}$$

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$$C_{\mathrm{TR}} = R_{\mathrm{TR}} \cdot C_{equ} \tag{21}$$

The depreciable residual value of fixed assets C_{R} is the residual value of fixed assets at the time of reaching the depreciable life, which is equal to the depreciation residual ratio multiplied by the investment in fixed assets (subscript L represents lines and subscript T represents main transformers, respectively).

5. Example analysis

5.1 Basic data

Taking a municipal 220 kV power network as an example, based on the load and power supply level of the original grid plan, the impact of demand response on the load of this grid and the impact of renewable energy power plants and energy storage plants on the power supply output is considered. It can be divided into five scenarios according to the proportion of energy storage allocation and the proportion of demand response participation, details of which are shown in Table 1.

Table 1. Scenario Settings.

Planning Scenarios	Energy storage configuration ratio	Demand-side resources ratio
Scenario 1 - Baseline Scenario	10%	10%
Scenario 2 - Low energy storage scenario	5%	10%
Scenario 3 - High Energy Storage Scenario	15%	10%
Scenario 4 - High Demand Response Scenario	10%	12.5%
Scenario 5 - Low demand response scenario	10%	7.5%

5.2 Analysis of planning results

Figure 1 and Figure 2 represent the number of capacity projects and the substation capacity demand under the original power grid planning and five scenarios, respectively. From the figures, it can be seen that after considering the adjustable comprehensive resources, the number and capacity of grid planning under the five scenarios have been improved. The highest construction number of planned project is 7 for scenario 5 and the lowest is 2 for scenario 4, which is less than half compared with 14 in the original planning report. And the planned project capacity of the grid for Scenario 1, Scenario 2, Scenario 3, Scenario 4, and Scenario 5 is reduced by 79%, 78%, 83%, 93%, and 75%, respectively, compared to the original planning capacity.

5.3 Evaluation of planning results

5.3.1 Reliability evaluation

The grid planning solutions under five different scenarios were subjected to tidal currents and short-circuit calculations, and “N-1” safety and stability analyses. The result shows that there are no line or equipment overloads occurred under the "N-1" calibration of the five scenarios; the short-circuit current levels of each voltage level were within the rated range. All five scenarios meet the reliability requirements.

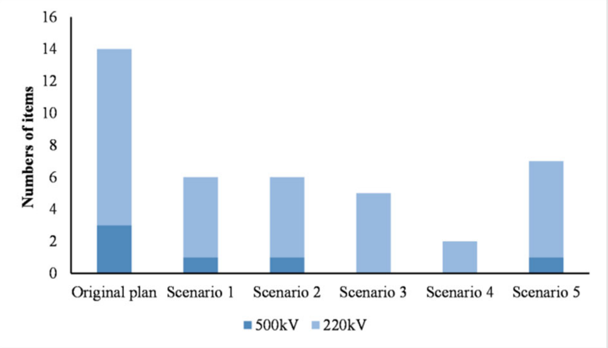

Figure 1 Number of network projects under different scenarios.

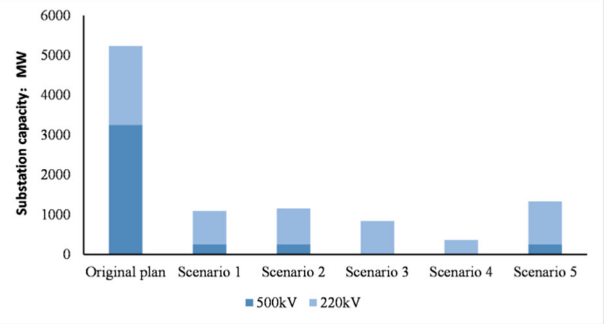

Figure 2 Capacity of power grid planning projects under different scenarios.

5.3.2 Economic evaluation

The economics of the grid planning scenarios under five different scenarios were evaluated, setting the operation period as 30 years, the conversion rate of fixed asset as 95%, the grid operation and maintenance rate as 2%, the compensation price of load shedding as 10 yuan/kw, and the discount rate as 8%, where the utilization cost of annual adjustable resources was mainly considered as the demand response cost. The economic benefits of each scenario were calculated and comparatively analyzed using the total investment during the planning period as well as the whole life cycle cost indicators. The results are shown in Table 2.

Comparing the total cost of the 5 scenarios and the original planning report in the planning period, it can be found that the total cost of the five scenarios considering adjustable comprehensive resources is lower than that in the original plan. Therefore, the integration of adjustable comprehensive resources into transmission network planning can reduce the grid investment cost in the planning period to a certain extent. And there is a more obvious improvement in investment efficiency, in which the most obvious improvement is scenario 4, followed by scenarios 3 and 1.

The sensitivity analysis of different scenarios shows that in this transmission network planning, for every 1 MW increase in energy storage capacity, the average reduction in construction investment is 390,800 RMB and the average reduction in total whole life cycle cost is 465,500 RMB. For every 1 MW increase in demand response capacity, the average reduction in construction investment is 872,100 RMB and the average reduction in total whole life cycle cost is 911,200 RMB. Overall, the effect of demand response resources utilization on grid planning investment is better than that of energy storage configuration, and almost no preliminary project investment is required.

In summary, the planning method of considering adjustable comprehensive resources is conducive to improving the economics and reliability of network operation. In particular, scenario 4 with the highest proportion of demand response participation has the best economy, which can bring higher investment efficiency and greater economic benefits to power grid companies.

Table 2. Economic comparison of various scenarios planning schemes.

Planning Scenario	New load during planning period (MW·h)	Construction investment (10^4 yuan)	Unit investment to increase the supply load (MW·h / 10^4 yuan)	Annual Operations and Maintenance Cost (10^4 yuan)	Annual adjustable comprehensive resources utilization cost (10^4 yuan)	Total Life-Cycle Cost (10^4 yuan)
Original plan	1591.2	118352.8	0.0134	2248.70	0	140980.73
Scenario 1	1435.2	32032.8	0.0448	608.62	431.81	42502.28
Scenario 2	1435.2	34832.8	0.0412	661.82	431.81	45837.61
Scenario 3	1435.2	28775.2	0.0499	546.73	431.81	38621.86
Scenario 4	1396	15975.2	0.0874	303.53	630.11	25370.14
Scenario 5	1474.4	36432.8	0.0405	692.22	332.65	46745.75

6. Conclusion

This paper proposed a novel transmission grid framework considering adjustable comprehensive resources under the new power system, and used a municipal grid as an example for planning and evaluating the novel transmission network. The results showed that all types of adjustable comprehensive resources have a certain degree of substitution for conventional power in grid planning, and in particular, demand response resources have the most significant available potential. Therefore, this paper made the following recommendations. (1) Consider the role of adjustable resources in grid planning and use them as an alternative resource on the generation side for transmission grid planning; (2) Explore user-oriented demand response models and improve the subsidy mechanism to guide users to actively participate in demand response; (3) Promote the application of big data in transmission grid planning, strengthen data governance, and improve the load classification statistics function of the mining system. Additionally, use data-driven statistics to depict the uncertainty factors, operation modes and scenarios in the planning process.

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