Optimal Capacity Proportion and Distribution Planning of Wind, Photovoltaic and Hydro Power in Bundled Transmission System

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Abstract. The wind, photovoltaic and hydro power bundled transmission system attends to become common in Northwest and Southwest of China. To make better use of the power complementary characteristic of different power sources, the installed capacity proportion of wind, photovoltaic and hydro power, and their capacity distribution for each integration node is a significant issue to be solved in power system planning stage. An optimal capacity proportion and capacity distribution model for wind, photovoltaic and hydro power bundled transmission system is proposed here, which considers the power out characteristic of power resources with different type and in different area based on real operation data. The transmission capacity limit of power grid is also considered in this paper. Simulation cases are tested referring to one real regional system in Southwest China for planning level year 2020. The results verify the effectiveness of the model in this paper.

1. Introduction
China’s wind and photovoltaic power have experienced rapid development in recent years. Until the end of 2015, the installed capacity proportions of wind and photovoltaic power in China have increased to 8.6% and 2.9%, respectively [1-2]. In some provinces in Northwest and Southwest of China which also have rich hydro power resource, the wind, photovoltaic and hydro power bundled transmission system is becoming more and more common. For example, in 2020, the installed capacity for wind, photovoltaic and hydro power in Sichuan province will increase to 85760MW, 7000MW and 3000WM. Then, the power system in Sichuan province will become the largest wind, photovoltaic and hydro power bundled transmission system in China.

The power output among wind, photovoltaic and hydro power often shows complementary characteristic [3]. The power output of wind and photovoltaic power are relatively high in winter and relatively low in summer. Which the power output of hydro power has the opposite feature, which shows great complementary characteristic for wind and photovoltaic. This complementary characteristic can be used to reduce the electric quantity shortage during dry season because of the low hydro power output and increase the utilization rate of transmission lines.

In order to make the best use of their power output complementary characteristics, the optimal installed capacity proportion of wind, photovoltaic and hydro power should be decided during planning stage in these systems. In addition, the installed capacity distribution of wind, photovoltaic and hydro power for each integration node should also be optimized. Significant relevant researches...
have been done related to this issue. Literature [4] presents a method that derives the optimal renewable generation mix from hydro, wind and photovoltaic. However, the power output constraints for wind, photovoltaic and hydro power and the power network constraints are not considered in this paper. In addition, the installed capacity distribution of different power generation technology for each node is not mentioned in [4]. The seasonal optimal mix between wind and solar power generation to minimum the required stored energy is studied in [5]. A size optimization for a hybrid photovoltaic-wind energy system is proposed in [6], which can decide the installed capacity of wind and photovoltaic power under different constraints. However, the timing sequence characteristics for wind and photovoltaic’ power output cannot be considered in this model. Literature [7] proposed a method to optimize the installed capacity for wind and photovoltaic based on timing simulation, but it is conducted based on wind and photovoltaic power output characteristic obtained through simulation model, rather than the real power output data. As an improvement for [7], a stratified optimization algorithm for optimal proportion of wind and solar based on real power output data is presented in [8]. However, the installed capacity distribution of different power generation technology for each node cannot be obtained using this method. A flexible robust optimization model with adjustable uncertainty budget is built for wind/photovoltaic/hydro/thermal hybrid power system to achieve coordination between reliability and economy is proposed in [9]. However, this model can only adapt to the dispatch problem in operation stage.

An optimal capacity proportion and capacity distribution model for wind, photovoltaic and hydro power bundled transmission system is proposed in this paper. This model considers the power output characteristic of wind, photovoltaic and hydro power for different integration area based on real power output data. The transmission capacity limits for power grid are also considered in this model. Usually, the capacity and type of hydropower stations are determined by watershed planning, and some of the hydro power stations have already built. Therefore, it is assumed that the capacity and type of hydropower stations are known in this paper. The corresponding optimal capacity proportion and capacity distribution for wind and photovoltaic power are studied here. The remainder of this paper is organized as follows: Section II details the concept of wind, photovoltaic and hydro power bundled transmission system. Section III analyzes the power output complementary characteristics for wind, photovoltaic and hydro power. The optimal capacity proportion and capacity distribution model is proposed in section IV and the simulation cases based on real power system are conducted in section. Finally, conclusions are drawn in Section VI.

2. Wind, photovoltaic and hydro power bundled transmission system
In these bundled transmission system, the wind, photovoltaic and hydro power are often transmitted together through high voltage dc transmission lines (UHVDC) to load center. To keep safety and maintain service life of DC equipment, the transmitted power through UHVDC should keep stable and track scheduled power curve. In daily operation, the regulation capability of hydro power could help to reduce the power output fluctuation from wind and photovoltaic power, which increase the power curve tracking capability of this system. In annual operation, the electric quantity complementary characteristics among different power sources for different months can increase the utilization rate of the UHVDC transmission lines.

3. Analysis of complementary characteristic
In order to study the technical feasibility of wind, photovoltaic and hydro power bundled transmission, the complementary power output characteristics of them are analyzed.

3.1. Annual complementary characteristic
The annual power output curves of wind, photovoltaic and hydro power of one province in southwest China are shown in figure 1. It can be seen that the annual power output curves of wind and hydro power have one peak and one valley, respectively. However, the peak of wind power and the valley of hydro power occur at the same time, which shows great complementary characteristic. The difference
of photovoltaic power output among different months is relatively low, but it also shows complementary characteristic for wind and hydro power.

![Figure 1](image1)

**Figure 1.** Annual power output characteristic of wind power, photovoltaic power and hydro power

3.2. *Daily complementary characteristic*

The typical daily power output curves of wind, photovoltaic and hydro power for wet season of one province in southwest China are shown in figure 2. The photovoltaic power output is mainly concentrated from 9:00 to 18:00 and reduces to zero in the evening. While the daily wind power output has opposite characteristic comparing to photovoltaic power, which shows complementary characteristic. The daily power output curve of hydro power is relatively stable, but it also shows complementary characteristic for wind power.

![Figure 2](image2)

**Figure 2.** Daily power output characteristic of wind power, photovoltaic power and hydro power

4. *Optimal capacity proportion and capacity distribution planning model*

4.1. *Scheduled power curve of HVDC*

The scheduled power curve of HVDC is determined refer to the actual DC operation curve of one province in southwest China. In wet season, the transmitted power of HVDC is equal to its rated capacity. In dry season, the maximum transmitted power of HVDC is about 0.45 times of rated capacity. Besides, the transmitted power for dry season is higher during peak-load time period and lower during other time period. The typical HVDC transmission curve considered in the simulation cases are shown in figure 3 and figure 4.

![Figure 3](image3)

**Figure 3.** Transmitted power of HVDC for dry season
The normalized timing power output curves of wind and photovoltaic power are obtained according to the historical power output curve of existing wind farms and photovoltaic power stations in each integration area of the simulation system. The normalized timing power output curve of one hydro power station is obtained using its historical power output curve. The difference of power output characteristic of one hydro power station with or without regulation capability has already been considered in its power output curve.

4.3. Capacity Proportion and Distribution Optimal Model

The model to find out optimal capacity proportion and capacity distribution of wind, photovoltaic and hydro power is proposed here. The optimal results are obtained through annual timing simulation using this model. The time resolution for simulation is considered as one hour here. The scheduled power curve of UHVDC, the power output characteristics of wind, photovoltaic and hydro power, the transmission limit of key AC transmission section are all considered in the constraints.

4.3.1. Objective function. The objective of this model is to minimize the abandoned electric quantity for wind, photovoltaic and hydro power during one year. In addition, the objective also attends to minimize the construction costs for newly built wind power and photovoltaic capacity. (see (1)).

\[
\begin{align*}
\min & \sum_{i=1}^{D} \sum_{t=1}^{T} \left( \rho_w \sum_{k=1}^{N_{k,w}} C_{w,i} (t) \Delta T + \rho_v \sum_{k=1}^{N_{k,v}} C_{v,i} (t) \Delta T + \rho_h \sum_{k=1}^{N_{k,h}} C_{h,i} (t) \Delta T + \rho_e e(t) \right) \\
+ & \sum_{k=1}^{N_{k,v}} \alpha_{v,i} M_{v,i} + \sum_{k=1}^{N_{k,w}} \alpha_{w,i} M_{w,i}
\end{align*}
\]

Where, \( D \) denotes the number of days for simulation, which is equal to 365 here. \( T \) denotes the number of time period in one day, which is equal to 24 here. \( \Delta T \) (hour) is the time resolution for simulation and considered as 1 hour here. \( N_{k,v}, N_{k,w} \) are the number of integration nodes for photovoltaic and wind power. \( N_{k,h} \) is the number of hydro power’s integration nodes. \( C_{v,i} (t), C_{w,i} (t), C_{h,i} (t) \) (MW) are the abandoned wind, photovoltaic and hydro power at node \( k, i, j \) for time period \( t \), respectively. \( \rho_w, \rho_v, \rho_h \) (CNY/MWh) are the penalty weighting factors for abandoned wind, photovoltaic and hydro power, respectively. Considering that \( \rho_v > \rho_w > \rho_h \), therefore the priority order for electric quantity utilization is photovoltaic power first, wind power second and hydro power the last. \( M_{v,i}, M_{w,i} \) (MW) are the installed capacity of photovoltaic and wind power at node \( k, i \), respectively. \( \alpha_{v,i}, \alpha_{w,i} \) (CNY/MW) is the per capacity construction cost for photovoltaic and wind power at node \( k, i \), respectively. \( \alpha_{v,i}, \alpha_{w,i} \) are decided considering the resource condition and the difficulty for construction. \( e(t) \) (MW) is the power shortage variable for HVDC transmission curves and \( \rho_e \) is the punishment cost for it. \( \rho_e \) is selected as a large number to track the transmission curve as much as possible.
4.3.2 Constraint conditions. Power balance constraints

\[
\min \sum_{i,j} \left( \rho \sum_{t} C_{s,i}(t) \Delta t + \rho \sum_{t} C_{s,j}(t) \Delta t + \rho \sum_{t} C_{d,i}(t) \Delta t + \rho(t) \right) \\
+ \sum_{i,j} M_i \Delta t + \sum_{i,j} M_j \Delta t
\]

Where, \( N_j \) is the number of load node. \( P_{s,i}(t) \), \( P_{s,j}(t) \), \( P_{d,j}(t) \) (MW) are the power output of photovoltaic, wind and hydro power at node \( k \), \( i,j \) for time period \( t \), respectively. \( P_{int,d}(t) \) (MW) is the load power at node \( d \) for time period \( t \). \( P_{dc,m}(t) \) (MW) is the transmitted power through HVDC transmission line \( n \) for time period \( t \) according to scheduled power curve in Section IV-B. \( P_{ac,m}(t) \) (MW) is the transmitted power through AC transmission section \( m \) for time period \( t \). For simplicity, it is considered that \( P_{dc,m}(t) = 0.9P_{dc,m}^{lim} \) during wet season and \( P_{ac,m}(t) = 0.5P_{ac,m}^{lim} \). \( P_{ac,m}^{lim} \) (MW) is the maximum operation transmission capability of AC transmission section decided by dispatch center.

Power output constraints for wind and photovoltaic power

The power output constraints for photovoltaic power at integration node \( k \) and wind power at integration node \( i \) are shown in equation (3) and (4). The range of optimization variables are shown in equation (5) and (6).

\[
P_{s,i}(t) + C_{s,i}(t) = M_{s,i}P_{s,i}^\ast(t)
\]

\[
P_{s,j}(t) + C_{s,j}(t) = M_{s,j}P_{s,j}^\ast(t)
\]

\[
P_{s,i}(t) \geq 0, C_{s,i}(t) \geq 0, M_{s,i} \geq 0
\]

\[
P_{s,j}(t) \geq 0, C_{s,j}(t) \geq 0, M_{s,j} \geq 0
\]

Where, \( P_{s,i}^\ast(t) \), \( P_{s,j}^\ast(t) \) (p.u.) are the normalized power outputs of photovoltaic and wind power at node \( k \), \( i \) for time period \( t \), respectively. \( P_{s,i}^\ast(t) \), \( P_{s,j}^\ast(t) \) are obtained using the method in Section IV-C.

Power output constraints for hydro power stations

The power output constraints for hydro power stations are shown in equation (7)-(8). The difference of power output characteristics between hydro power station with or without reservoir is considered in its normalized power output curve.

\[
P_{s,i}(t) + C_{s,i}(t) = m_{h,i}P_{h,i}^\ast(t)
\]

\[
P_{s,i}(t) \geq P_{h,i}^{min}, C_{s,i}(t) \geq 0
\]

Where, \( P_{h,i}^\ast(t) \) (p.u.) is the normalized power output of hydro power station \( j \) for time period \( t \). \( P_{h,i}^{min} \) (MW) is the forced power output of hydro power station \( j \). \( m_{h,i} \) (MW) is the installed capacity of hydro power station \( j \). \( m_{h,i} \) is determined by river basin planning and it is a constant here.

Installed capacity constraints

The installed capacity constraints for photovoltaic and wind power at node \( k \), \( i \) are shown in equation (9)-(10).

\[
m_{s,i} \leq M_{s,i} \leq m_{s,i}^{max}
\]

\[
m_{w,i} \leq M_{w,i} \leq m_{w,i}^{max}
\]

Where, \( m_{s,i}, m_{w,i} \) (MW) are the current installed capacity for photovoltaic and wind power at node \( k \), \( i \). \( m_{s,i}^{max}, m_{w,i}^{max} \) (MW) are the maximum installed capacity for photovoltaic and wind power at node \( k \), \( i \), constrained by the economic development capacity of wind and photovoltaic power in this area.
The Transmission limit constraints for transmission power grid are also considered in this model.

5. Simulation case

5.1. Introduction for simulation system

The simulation system is built referring to one real regional system in Southwest China for planning level year 2020, as is shown in figure 5. The total installed capacity of hydro power in this simulation system is 25000MW. The hydro power stations integrate from node 2, 3, 4, 5, 6, 7 and 11, respectively. Hydro power stations at node 3, 6 and 11 have reservoirs and can provide good regulating capability. Considering the actual available resource, the wind and photovoltaic power integrate from node 5, 6, 8, 10, 12 and 13, respectively. The installed capacities of wind and photovoltaic in each node are optimized in this paper. The peak load of this simulation system is considered as 3800MW during wet season and 3200MW during dry season. The maximum operation transmission capability of AC transmission section is 6000MW here. The rated capacities of HVDC1 and HVDC2 are 6500MW and 7200MW, respectively. The electricity prices of wind, photovoltaic and hydro power are selected as \( \rho_w = 880 \text{(CNY/MWh)} \), \( \rho_v = 580 \text{(CNY/MWh)} \), \( \rho_h = 300 \text{(CNY/MWh)} \).

![Figure 5. Simulation system](image)

5.2. Capacity proportion planning results

The optimal capacity planning results of wind and photovoltaic power for each node are shown in Table 1. It can be seen that the total installed capacity proportion of hydro power, wind power and photovoltaic power are 77%, 19.7% and 3.3%, respectively. Most wind power integrate from node 6, 8 and 12 because of the rich mountain wind resource condition there. The installed capacity of photovoltaic power for each node has very small difference because the similar photovoltaic resource condition.

| Node | Wind (MW) | Photovoltaic |
|------|-----------|--------------|
| 5    | 750       | 230          |
| 6    | 1850      | 260          |
| 8    | 1000      | 200          |
| 10   | 800       | 100          |
| 12   | 1200      | 190          |
| 13   | 800       | 100          |
| Total| 6400(19.7%)| 1080(3.3%)   |

The one year operation simulation results using the capacity planning results in Table 1 are shown in Table 2. There are no abandoned wind and photovoltaic power during one year operation because of the prior dispatch right for them. The abandoned hydroelectric quantity proportion is 6.9%, which
often happens when the power output for wind and photovoltaic power is high during wet season. The power shortage quantity proportion for HVDC transmission curves is 0.3%, which often happens when the power output for wind and photovoltaic power is low during dry season.

### Table 2. One year operation simulation results

| Abandoned rate for wind power (%) | Abandoned rate for photovoltaic power (%) | Abandoned rate for hydro power (%) | Power shortage rate for HVDC transmission curves (%) |
|----------------------------------|-----------------------------------------|----------------------------------|-----------------------------------------------|
| 0                                | 0                                       | 6.9                              | 0.3                                           |

The electric quantity proportions of wind, photovoltaic and hydro power for each month during one year operation simulation are shown in figure 6. During wet season, the electric quantity proportions of hydro power are mainly larger than 90%, while the electric quantity proportions of wind and photovoltaic power are smaller than 10% and 1%, respectively. During dry season, the electric quantity proportions of hydro power reduce to smaller than 80%, which the electric quantity proportions of wind and photovoltaic power increase to around 20% and 2.5%, respectively. The results show that the electric quantity wind, photovoltaic and hydro power shows great complementarity during one year.

![Figure 6. Electric quantity proportions of wind, photovoltaic and hydro power](image)

### 5.3. Influence of capacity proportion for wind, photovoltaic and hydro power on operation results

In order to analyze the influence of different installed capacity proportion for wind, photovoltaic and hydro power in the one year operation results, the following two cases are studied. The capacity proportion result obtained using the method in this paper (see Table 2) is named as benchmark in the following simulation cases.

#### 5.3.1 Case A: Influence of hydro power installed capacity proportion

For all the simulation cases in case A, the total installed capacity of this system is kept unchanged, which is equal to benchmark (32480MW). In addition, the installed capacity proportion between wind and photovoltaic power is also keeps unchanged, which is equal to benchmark (wind installed capacity / photovoltaic installed capacity is equal to 6/1). The hydro power installed capacity proportion increases from 60% to 95% for different simulation cases. The installed capacity information of different examples in case A is shown in table 3.

### Table 3. Installed capacity information of different examples in case A

| Simulation cases name | Installed capacity for wind power (MW) | Installed capacity for photovoltaic power (MW) | Capacity of wind power: Capacity of photovoltaic power | Installed capacity for hydro power (MW) |
|-----------------------|---------------------------------------|-----------------------------------------------|------------------------------------------------------|---------------------------------------|
| CaseA.1               | 11141(34.3%)                          | 1851(5.7%)                                     | 6:1                                                 | 19488(60%)                           |
| CaseA.2               | 8347(25.7%)                           | 1397(4.3%)                                     | 6:1                                                 | 22736(70%)                           |
| **Benchmark**         | **6400(19.7%)**                       | **1080(3.3%)**                                 | **6:1**                                             | **25000(77%)**                       |
| CaseA.3               | 4157(12.8%)                           | 715(2.2%)                                      | 6:1                                                 | 27608(85%)                           |
| CaseA.4               | 1397(4.3%)                            | 227(0.7%)                                      | 6:1                                                 | 30856(95%)                           |

The one year operation simulation results of examples in table 3 are shown in table 4.
Table 4. Simulation results for Case A

| Simulation cases name | Abandoned rate for wind electric quantity (%) | Abandoned rate for photovoltaic electric quantity (%) | Abandoned rate for hydro electric quantity (%) | Power shortage rate for HVDC transmission curves (%) |
|-----------------------|---------------------------------------------|-----------------------------------------------------|-----------------------------------------------|-----------------------------------------------------|
| CaseA.1               | 1.1                                         | 0                                                   | 5.7                                           | 8.6                                                 |
| CaseA.2               | 0                                           | 0                                                   | 6.0                                           | 2.9                                                 |
| **Benchmark**         | **0**                                       | **0**                                               | **6.9**                                       | **0.3**                                             |
| CaseA.3               | 0                                           | 0                                                   | 12.4                                          | 0.1                                                 |
| CaseA.4               | 0                                           | 0                                                   | 15.8                                          | 0                                                   |

Table 4 shows that when the capacity proportion of hydro power is too low, the power shortage rates for the HVDC transmission curves increases a lot, which reduce the operation safety of the system. On the contrary, when the capacity proportion of hydro power is too high, the abandoned rate for hydroelectric quantity increases obviously, which reduce the operation economy for hydro power. Therefore, the capacity proportion for wind, photovoltaic and hydro power obtained in this paper can balance the operation safety and economy for this system.

5.3.2 Case B: Influence of installed capacity proportion between wind and photovoltaic power. For all the simulation cases in case B, the total installed capacity of this system is kept unchanged, which is equal to benchmark (32480MW). In addition, the installed capacity of hydro power is kept unchanged, which is equal to benchmark (25000MW). The installed capacity proportion between wind and photovoltaic power increases from 1:6 to 6:1 for different simulation cases. The installed capacity information of different examples in case B is shown in table 5.

Table 5. Installed capacity information of different examples in case B

| Simulation cases name | Installed capacity for wind power (MW) | Installed capacity for photovoltaic power (MW) | Capacity of wind power: Capacity of photovoltaic power | Installed capacity for hydro power (MW) |
|-----------------------|----------------------------------------|-----------------------------------------------|--------------------------------------------------------|----------------------------------------|
| CaseB.1               | 1080(3.3%)                             | 6400(19.7%)                                   | 1:6                                                    | 25000(77%)                            |
| CaseB.2               | 1870(5.7%)                             | 5610(17.3%)                                   | 1:3                                                    | 25000(77%)                            |
| CaseB.3               | 3740(11.5%)                            | 3740(11.5%)                                   | 1:1                                                    | 25000(77%)                            |
| CaseB.4               | 5610(17.3%)                            | 1870(5.7%)                                    | 3:1                                                    | 25000(77%)                            |
| **Benchmark**         | **6400(19.7%)**                        | **1080(3.3%)**                                | **6:1**                                                | **25000(77%)**                        |

The one year operation simulation results of examples in table 5 are shown in table 6.

Table 6. Simulation results for Case A

| Simulation cases name | Abandoned rate for wind electric quantity (%) | Abandoned rate for photovoltaic electric quantity (%) | Abandoned rate for hydro electric quantity (%) | Power shortage rate for HVDC transmission curves (%) |
|-----------------------|---------------------------------------------|-----------------------------------------------------|-----------------------------------------------|-----------------------------------------------------|
| CaseB.1               | 0                                           | 0                                                   | 7.8                                           | 2.8                                                 |
| CaseB.2               | 0                                           | 0                                                   | 7.4                                           | 2.1                                                 |
| CaseB.3               | 0                                           | 0                                                   | 7.3                                           | 1.2                                                 |
| CaseB.4               | 0                                           | 0                                                   | 7.1                                           | 0.7                                                 |
| **Benchmark**         | **0**                                       | **0**                                               | **6.9**                                       | **0.3**                                              |

Table 6 shows that when the installed capacity proportion between wind and photovoltaic power increases, the power shortage rate for HVDC transmission curve and the amount of abandoned hydro reduce. The results indicate that wind power has better complementarity with hydro power comparing to photovoltaic power, so that the operation safety and economy increase when wind power capacity proportion increases.
6. Conclusion
As the policy to encourage the development of renewable energy, the wind, photovoltaic and hydro power bundled transmission system becomes common in Northwest and Southwest of China. In order to obtain the optimal installed capacity proportion for wind, photovoltaic and hydro power, and their capacity distribution for each integration node, an optimal model based on timing simulation is proposed here. The objective of this model is to minimize the overall abandoned wind, photovoltaic and hydro power for one year, and minimize the construction cost for newly built wind and photovoltaic power installed capacity.

Simulation cases are conducted based on one real regional system in Southwest China for planning level year 2020. It is found that the capacity proportion and capacity distribution results obtained using the method proposed here presents better performance to keep operation safety and economy comparing to other results. This highlights the effectiveness and the importance of the method proposed in this paper.

7. References
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