

Article

Capacity Planning Method for Wind–Solar–Thermal-Storage Bundled HVDC Sending System Considering Transient Overvoltage Constraints

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Abstract: High-voltage direct current (HVDC) sending systems have been the main means of renewable power cross-regional sharing and consumption. However, the transient overvoltage problems restrict the transmission capacity and renewable energy accommodation. The allocation of wind–solar–thermal storage capacity has become an important factor affecting the safety and stability of renewable energy sending. A capacity planning method is proposed for a wind–solar–thermal-storage bundled HVDC sending system considering transient overvoltage constraints. Firstly, based on quantile regression analysis and Gaussian mixture modeling, the typical scenario generation method is proposed to depict the uncertainty of renewable energy. Then, the transient overvoltage characteristics of the integrated HVDC transmission system are analyzed. The relationship between the power output of power sources and the system short-circuit capacity is derived. Meanwhile, the calculation method of the minimum short-circuit capacity of the HVDC system is proposed. Based on the calculation method, the transient overvoltage constraint corresponding to the voltage support strength is constructed. Finally, considering the transient overvoltage constraints, the capacity planning model of the wind–solar–thermal storage is established. The upper-layer model optimizes the configuration scheme of the wind–solar–thermal storage to minimize the total system cost. The lower-layer model optimizes the operation scheduling under the typical operation scenarios of renewable energy and delivery load. The optimal capacity planning scheme for the wind–solar–thermal storage is determined through the coordinated optimization of the two-layer model. The feasibility and effectiveness of the proposed method are verified through a case analysis. The results show that the proposed planning method can effectively maintain a higher short-circuit ratio and improve the voltage support strength under the premise of completing the sending plan.

Keywords: transient overvoltage; short-circuit capacity; wind–solar–thermal storage; HVDC sending system; planning methods



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1. Introduction

With the development of the global energy system showing a trend towards decarbonization, increasing the proportion of renewable energy generation has become an important part of reducing carbon emissions and energy transformation in the power system. By the end of 2023, the global installed capacity of renewable energy generation reached 3865 GW, and the growth rate is 14.6%. Wind power comprises 1017 GW, and solar power is at 1419 GW. In addition, the global coal-fired power generation is 10,513 TWh,

accounting for 35.13%. In China, the installed capacity of coal-fired power generation accounts for 47.61%, and the proportion is gradually decreasing. The installed capacity of wind power and photovoltaic reached 441 GW and 609 GW by the end of 2023, respectively. Wind and solar power generation is gradually becoming the main force of power generation in China. Due to the inherent stochasticity and fluctuation in renewable energy generation, the large-scale development of renewable energy poses challenges to the security and stability of the power grid [1,2]. Cross-regional power transmission is crucial for the consumption of renewable energy. In recent years, many high-voltage direct current (HVDC) transmission systems have been constructed in China and have become the main means of renewable power cross-regional transmission. But when short-circuit faults such as DC blocking occur in the HVDC systems, a large amount of surplus reactive power will be sent back to the AC system and lead to transient overvoltage [3]. This may lead to the off-grid accident of renewable energy. To ensure the reliability of system operation and promote the consumption of renewable energy, the power system needs to utilize a variety of resources to improve the flexible adjustment ability and realize the stable operation of the system.

The stability of the power system means the ability of the power system to maintain stable operation after being disturbed. With the extensive integration of converter-interfaced devices, the operation behavior of the power system has significantly changed [4,5]. In [6], the characteristics of power system stability are thoroughly analyzed and classified. The HVDC lines are an important factor affecting static and dynamic voltage stability. In [7], the transient stability estimation method based on machine learning is proposed to analyze the operation performance of the islanded microgrids. Transient stability studies are a vital factor in the operational analysis and planning optimization of power systems. In addition, the influence of HVDC transmissions cannot be ignored [8]. In [8], the HVDC coordination control strategy considering the transient voltage limits is proposed to guarantee the operation stability of the receiving-end grid. The transient voltage problem under DC near-field faults is prominent [9]. The sending-end systems with a high proportion of new energy face a high risk of disconnection. The transient voltage problem has become an important factor restricting the further development of new energy [10]. The short-circuit ratio (SCR) is strongly related to the system voltage strength and influences the transient overvoltage caused by DC blocking [11]. For the HVDC sending system, commutation failures can result in transient voltage and pose a threat to the normal operation of the wind turbine [12,13]. In addition, DC blocking also leads to abundant surplus reactive power and a serious overvoltage issue [14]. To guarantee the voltage security constraints under DC faults, much research has been carried out on system planning [15], influence factors analysis [16], and short-term scheduling [17]. In [18], a synchronous condensers planning method is proposed to optimize the size and allocation of synchronous condensers. The SCR is considered in the planning model to guarantee the power system's strength. The accommodation capacity assessment method for grid-following converters is proposed in [19], and the SCR constraints are utilized to improve grid strength. In [20], the unit commitment model considering the short-circuit current constraint is established. The economy and security of the power system operation can be guaranteed. In [21,22], the SCR and voltage security constraints of renewable energy stations are constructed and embedded in the unit commitment model to avoid off-grid wind turbines accidents. The relationship between the short-term scheduling and short-circuit current level is analyzed. With the increase in renewable energy permeability, the system voltage strength has decreased, and the transient voltage problem should be investigated in the planning and operation stage. Meanwhile, HVDC transmission plays an important role in the sharing

of renewable energy, and the generation resources of integrated resource-sending power systems should be reasonably planned considering the economy and security.

The research on AC/DC hybrid system planning problems has considered flexible resource configurations, economy optimization, and voltage security constraints. In [23], the multiple-resources flexibility planning method is proposed to cope with the stochasticity and intermittent nature of renewable energy. The coordination of source-grid-load-storage resources can achieve the tradeoff between cost-effectiveness and flexibility. A stochastic planning strategy for renewable energy and energy storage is proposed in [24]. Pumped hydro storage and thermal energy storage can effectively improve the economics and flexibility. With the development of renewable energy in China, power system operators should pay great attention to the demand for system flexibility and increase the proportion of flexible resources to enhance system flexibility. For the HVDC sending system, the thermal generators and wind generation are coordinated to plan and satisfy the sending power demand [25]. A stochastic transmission configuration method for AC/DC hybrid systems is proposed in [26]. In [27], the network planning model considering the operational reliability of the HVDC grid is established. To improve the utilization of renewable energy, a robust network and energy storage coordination configuration method is proposed in [28]. In [29], the hydro–wind–solar-storage bundling system coordination planning model is established to improve the penetration level of renewable energy. In [30], a multi-objective planning model of HVDC lines and power-to-hydrogen devices is established for inter-regional power sharing. Therefore, wind and thermal storage capacity allocation considering the renewable energy sending strategy has also become an important research field with significant application value. The above literature is mostly centered on system economics and renewable energy consumption. However, large-scale renewable energy integration may cause transient overvoltage when sent out by HVDC. How to mitigate the impact of transient overvoltage and improve the security of the HVDC sending system is a problem that needs to be investigated urgently.

To solve the above problems, this paper proposes a resource capacity planning method for wind–solar–thermal-storage bundled HVDC sending systems considering transient overvoltage constraints. Based on the transient overvoltage and the minimum short-circuit capacity, the transient overvoltage constraints are constructed to correspond to the voltage support strength. The capacity planning model of the integrated wind–solar–thermal storage with the transient overvoltage constraints is established. The feasibility and effectiveness of the proposed method are verified by a case analysis. The contributions of this paper are shown as follows:

- (1) A combination of quantile regression analysis and the Gaussian mixture model is proposed to generate the renewable energy scenarios to describe the uncertainty. Based on the typical operation scenarios, the configuration schemes of multiple generation resources can effectively cope with the uncertainty of renewable energy and meet the demand for sending load;
- (2) The transient overvoltage and influencing factors of the HVDC sending transmission system are analyzed. Further, the minimum short-circuit capacity calculation method of the system is proposed. Considering the voltage support strength, the transient overvoltage constraint is established. Compared with [25–29], the security constraints can be embedded in the planning model to guarantee transient stability under the DC faults;
- (3) The double-layer capacity planning model of the wind–solar–thermal-storage bundling HVDC sending system with transient overvoltage constraints is established. The optimal capacity configuration scheme for multiple generation resources is determined through the coordination of the two-layer model. Compared with [25–29],

the planning results can effectively coordinate inter-regional power sending, improve comprehensive benefits, and guarantee voltage security.

The rest of this paper is organized as follows: Section 2 presents the scenario generation methods for renewable energy. In Section 3, the transient overvoltage and influencing factors are analyzed. Section 4 depicts the relationship between renewable energy and power system strength. The layer planning model of the multiple-resources bundling sending system is given in Section 5. Case studies are shown in Section 6. Conclusions are shown in Section 7.

2. Typical Scenario Generation Methods for Renewable Energy

Wind power and photovoltaic power are characterized by high data complexity and large data volume. To accurately portray the uncertainty of renewable energy power and guarantee the safe and stable operation of the system, quantile regression (QR) and the Gaussian mixture model (GMM) are utilized to generate the typical scenarios [31]. A nonparametric probabilistic prediction model is built to process the renewable energy samples. The variables are characterized by features and regression situations. Taking wind power as an example, the linear fitting relationship between the actual power and forecast data of wind power is constructed, and the quantile regression fitting method is used to describe the linear mapping relationship.

$$p_{\tau,t}^{w,r} = a_{\tau} p_t^{w,f} + b_{\tau} \quad (1)$$

where $p_t^{w,f}$ is the predicted power for the wind sampling site; $p_{\tau,t}^{w,r}$ is the actual wind power data of the τ quantile; a_{τ} and b_{τ} are the quantile linear mapping parameters, respectively.

Based on quantile regression theory, the estimation of parameters a_{τ} and b_{τ} is expressed as the following optimization problem:

$$\min J_{\tau} = \sum_{d=1}^D \sum_{t=1}^T \phi(p_{\tau,t}^r - p_{\tau,t}^f) \quad (2)$$

$$\phi_{\tau}(x) = \begin{cases} \tau x & x \geq 0 \\ (\tau - 1)x & x < 0 \end{cases} \quad (3)$$

where J_{τ} is the objective function for quantile τ ; ϕ_{τ} is the detection function.

A nonparametric probabilistic prediction model is constructed. Based on the wind power prediction output $p_t^{w,f}$, the $p_{\tau,t}^{w,r}$ is obtained to correspond to τ_t^w .

$$p_{\tau,t}^{w,r} = \hat{a}_{\tau} p_t^{w,f} + \hat{b}_{\tau}, \quad \tau = 0.05, 0.1, \dots, 0.95 \quad (4)$$

where $\hat{a}_{\tau}$ and $\hat{b}_{\tau}$ are the parameter estimates, respectively. The resulting set of actual quantile points is utilized to portray the wind power output uncertainty.

The quantile τ_t^w corresponding to the actual wind power output $p_t^{w,r}$ is obtained by linear interpolation. The uniform distribution τ^w is converted to a standardized nontrivial distribution ψ^w . The historical actual wind power output sequence is converted to a multidimensional Gaussian distribution $N_K(\mu, \Sigma)$ for clustering. The GMM algorithm can estimate the samples as a linear superposition of the probabilities of the S multidimensional Gaussian distributions. The probability density function $f_{\text{GMM}}(x)$ can be shown as (5).

$$f(x)_{\text{GMM}} = \sum_{s=1}^S \omega_s N(x|\mu_s, \Sigma_s) \quad (5)$$

where ω_s is the weight of the Gaussian distribution s ; $N(x|\mu_s, \Sigma_s)$ is the probability density function of the Gaussian distribution s ; x is the sample and is estimated using the maximum expectation method.

The S multi-dimensional Gaussian distribution obtained after clustering is converted to a uniformly distributed vector. Based on the non-parametric prediction model, the quantile matrix is obtained, and the wind power scenario set is calculated by point-by-point linear interpolation. The photovoltaic output samples refer to the above process to generate the photovoltaic scenarios, without going into details.

3. Analysis of Transient Overvoltage and Influencing Factors of Wind–Solar–Thermal- Storage DC Sending System

The typical wind–solar–thermal-storage HVDC sending system is shown in Figure 1.

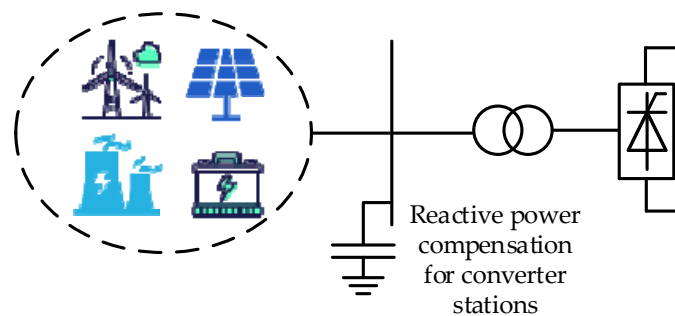


Figure 1. Schematic diagram of wind–solar–thermal-storage HVDC sending system.

The HVDC converter will consume a large amount of reactive power during normal operation, which is generally provided by the capacitor and AC filter in the converter station. The power balance relationship between the AC and DC systems during normal operation can be expressed as follows:

$$\begin{cases} P_{ac\_N} = P_{d\_N} \\ Q_{ac\_N} + Q_{Cr\_N} = Q_{d\_N} \end{cases} \quad (6)$$

where P_{ac_N} and Q_{ac_N} are the active power and reactive power fed into the converter station, respectively; P_{d_N} and Q_{d_N} are the active power and reactive power transmitted by DC, respectively; Q_{Cr_N} is the reactive power provided by the reactive power compensation device in the converter station; the subscript N denotes the normal operation state.

When the DC blocking fault occurs, the converter will not consume reactive power, and the resection of the reactive power compensation device needs 100 ms–200 ms. During this period, there will be a large amount of reactive power surplus in the sending-end system, which can be expressed as follows:

$$\Delta Q = Q_{ac\_N} + Q_{Cr} \quad (7)$$

In Equation (7), the relationship between Q_{Cr} and the commutation bus voltage on the rectifier side is shown as follows:

$$Q_{Cr} = U_{Lr,pu}^2 Q_{Cr\_rated} \quad (8)$$

where $U_{Lr,pu}$ is the converter bus voltage standardized value of the rectifier side; Q_{Cr_rated} is the rated value of the reactive power compensation device.

After DC blocking, the transient overvoltage of the rectifier side converter bus can be calculated as follows:

$$U_{Lr,pu} = 1 + \Delta U_{Lr,pu} = \frac{\Delta Q + S_C}{S_C} \quad (9)$$

According to Equations (7)–(9), it can be further calculated as follows [32]:

$$U_{Lr,pu} = -\sqrt{\left(\frac{S_C}{2Q_{Cr\_rated}}\right)^2 - \frac{Q_{ac\_N} + S_C}{Q_{Cr\_rated}}} + \frac{S_C}{2Q_{Cr\_rated}} \quad (10)$$

Due to the electrical distance between the wind farm and the converter bus in the sending system, the voltage $U_{Lw,pu}$ at the grid connection point of the wind farm after DC blocking should be constrained, as shown in (11).

$$U_{Lw,pu} \leq U_{Lr,pu} \quad (11)$$

From Equation (10), it can be seen that the transient overvoltage magnitude after DC blocking is mainly influenced by the rated value of the reactive power compensation device in the converter station Q_{Cr_rated} and the short-circuit capacity S_C at the converter bus. Generally speaking, the DC transmission power in the wind–solar–thermal-storage bundling DC sending system basically remains unchanged. Therefore, the reactive power consumed by the rectifier and Q_{Cr_rated} during normal operation basically will not have a large change. The wind–solar–thermal grid-connected capacities of the DC sending system have a large impact on S_C . From the planning point of view, the short-circuit capacity S_C at the converter bus is the dominant factor affecting the transient overvoltage amplitude.

4. Analysis of the Impact of New Energy Access on System Strength

The individual capacity of the wind turbine is P_w . The number of wind turbines in a single wind farm is n_w . The total installed capacity of the wind farm i is $P_{w\_total,i}$ and can be expressed as follows:

$$P_{w\_total,i} = n_w P_w \quad (12)$$

The number of thermal power generators in the DC sending system is N_g . The capacity of a single unit is P_T . The total installed capacity of thermal power is P_{T_total} and can be expressed as follows:

$$P_{T\_total} = N_g P_T \quad (13)$$

Assuming that the short-circuit capacity provided by the thermal power unit is k_{ST} , the DC-supporting thermal units are generally configured in the vicinity of the converter station. Therefore, it can be approximated that the equivalent electrical distance between the thermal units and the feeder converter bus is 0. The short-circuit capacity provided by the thermal power units at the converter bus is S_T and can be expressed as follows:

$$S_T = k_{ST} P_{T\_total} \quad (14)$$

Considering the confidence level of wind power output, the equivalent operating capacity of the wind farm is $P_{aw\_total,i}$ and can be expressed as Equation (15).

$$\begin{cases} P_{aw\_total,i} = K_{aw} P_{w\_total,i} \\ K_{aw} = c_w \frac{P_{w\_cf,i}}{P_{w\_total,i}} \end{cases} \quad (15)$$

where K_{aw} is the ratio of wind power start-up capacity to total installed capacity; c_w is the average wind power capacity correction factor and is taken as the reciprocal of the

wind power simultaneity rate; $P_{w\_cf,i}$ is the power output of the wind farm i at the given confidence level.

The ratio of the short-circuit capacity provided by the wind turbine at the grid connection point to the installed capacity is $k_{Sw,i}$. Figure 2 shows the equivalent schematic diagram of the wind farm.

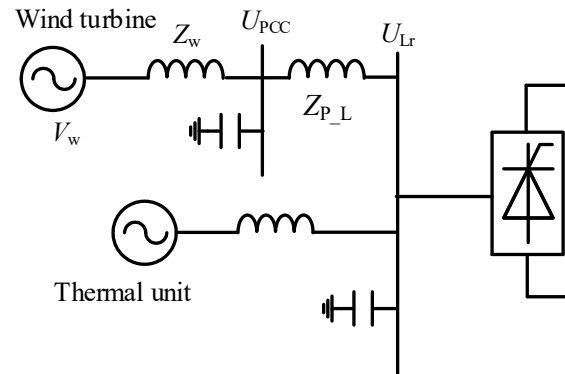


Figure 2. Equivalent schematic diagram of the wind farm.

In Figure 2, V_w is the equivalent electric potential of the wind farm and is equal to the voltage U_{PCC} at the PCC point; Z_w is the equivalent impedance of the wind farm; Z_{P_L} is the equivalent impedance of the wind farm to the converter busbar. The short-circuit capacity provided by the wind farm i at the grid connection point is $S_{w,i}$ and can be expressed as follows:

$$S_{w,i} = k_{Sw,i} P_{aw\_total,i} = \frac{U_{PCC,i}^2}{Z_{w,i}} \quad (16)$$

The short-circuit capacity provided by the wind farm i at the converter bus can be calculated as follows:

$$S_{w\_L,i} = \frac{U_{PCC,i}^2}{Z_{w,i} + Z_{P\_L,i}} \quad (17)$$

According to Equations (16) and (17), $S_{w\_L,i}$ can be calculated as follows:

$$S_{w\_L,i} = \frac{S_{w,i}}{1 + \frac{S_{w,i} Z_{P\_L,i}}{U_{PCC,i}^2}} \quad (18)$$

The short-circuit capacity analysis process for the photovoltaic power station is similar to that for wind farms and will not be repeated. The short-circuit current provided by the energy storage is limited. When the storage is far away from the short-circuit calculation point, the short-circuit capacity provided is negligible. The effect of energy storage is ignored. The short-circuit capacity provided by the wind–photovoltaic–thermal units at the converter bus can be expressed as follows:

$$S_C = \sum_{i=1}^{N_w} S_{w\_L,i} + \sum_{j=1}^{N_p} S_{p\_L,j} + S_T \quad (19)$$

where N_p and $S_{p\_L,i}$ are the number of the photovoltaic power stations and the short-circuit capacity provided by the individual photovoltaic plant, respectively.

5. Capacity Optimization Method of Wind–Solar–Thermal-Storage Bundled HVDC Sending System

5.1. The Planning Method for Wind–Solar–Thermal-Storage Bundled HVDC Sending System

Considering the transient overvoltage constraints, a dual-layer optimization planning method for the wind–solar–thermal-storage bundled HVDC sending system is proposed in Section 5. The optimal configuration of wind–solar–thermal storage is achieved. The framework of the planning strategy is shown in Figure 3. Firstly, considering the transient overvoltage characteristic and the short-circuit capacity, the transient overvoltage constraint corresponding to the voltage support strength is established. Then, the dual-layer planning model of the wind–solar–thermal-storage bundled HVDC sending system is established. The upper-layer model optimizes the configuration scheme of the multiple resources to minimize the total system cost. Considering the typical scenarios of renewable energy and delivery load, the lower-layer model optimizes the operation scheduling of wind–solar–thermal storage to guarantee power balance. Finally, the optimal capacity planning scheme for the wind–solar–thermal storage is determined through the coordinated optimization of the two-layer model.

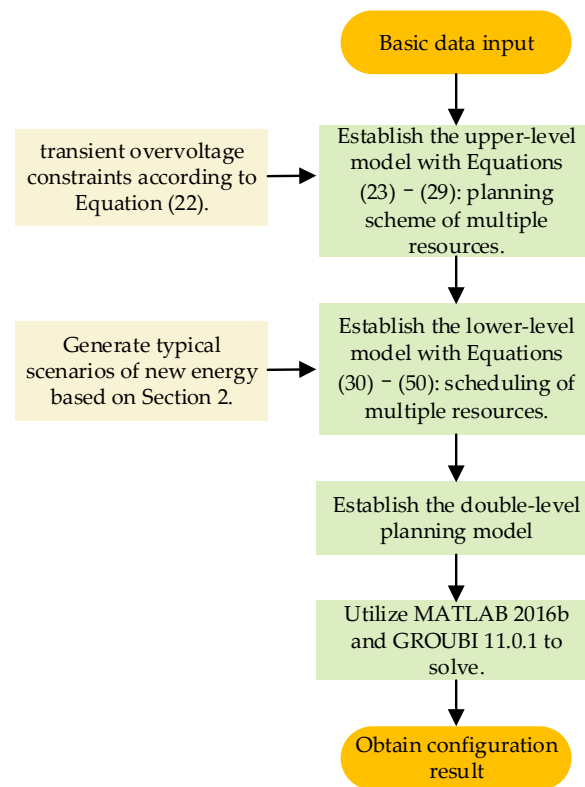


Figure 3. The framework of the planning method for wind–solar–thermal-storage bundled HVDC sending system.

5.2. Transient Overvoltage Constraints Based on Short-Circuit Capacity

The high-voltage ride-through capability of the wind turbine is U_{HVRT} . To ensure that the voltage at the wind turbine grid connection point does not exceed U_{HVRT} , the converter bus voltage due to the DC fault is $U_{Lr,pu}$ and should be constrained as follows:

$$U_{Lr,pu} \leq U_{HVRT} \quad (20)$$

According to Equations (9) and (10), the minimum short-circuit capacity S_{Cmin} can be calculated by the Equation (21).

$$S_{Cmin} = \frac{U_{HVRT}^2 Q_{Cr\_rated} + Q_{ac\_N}}{U_{HVRT} - 1} \quad (21)$$

Then, combining Equation (19) with Equation (21), the transient overvoltage constraints based on short-circuit capacity can be shown as follows:

$$\begin{cases} \sum_{i=1}^{N_w} S_{w\_L,i} + \sum_{j=1}^{N_p} S_{p\_L,j} + S_T \geq S_{Cmin} \\ \sum_{i=1}^{N_w} \frac{k_{Sw,i} P_{aw\_total,i}}{1 + \frac{k_{Sw,i} P_{aw\_total,i} Z_{P\_L,i}}{U_{PCC,i}^2}} + \sum_{j=1}^{N_p} \frac{k_{Sw,j} P_{ap\_total,j}}{1 + \frac{k_{Sw,j} P_{ap\_total,j} Z_{P\_L,j}}{U_{PCC,j}^2}} + k_{ST} P_{T\_total} \geq S_{Cmin} \end{cases} \quad (22)$$

5.3. Wind–Solar–Thermal–Storage Capacity Planning Model

5.3.1. Upper-Level Planning Model

The upper-level planning model aims to minimize the total system cost C_{total} , as shown in Equation (23). The total system cost includes the power investment cost C_{inv} , maintenance cost C_{maint} , and operation cost C_{op} .

$$\min C_{total} = C_{inv} + C_{maint} + C_{op} \quad (23)$$

$$\begin{cases} C_{inv} = d_{CRF}(N_{w1}C_w + N_{p1}C_p + N_gC_g) \\ d_{CRF} = r^d(1 + r^d)^k / ((1 + r^d)^k - 1) \end{cases} \quad (24)$$

$$C_{maint} = \sum_{j=1}^Y \sum_{g=1}^{N_g} \frac{K_g^{maint} C_{inv} (1 + r^{maint})^{j-1}}{1 / (1 + r^d)^{j-1}} \quad (25)$$

$$C_{op} = \sum_d^D C_{op,d}^{day} \quad (26)$$

where C_w , C_p , and C_g are the investment and construction costs of individual wind, photovoltaic, and thermal units; N_{w1} , N_{p1} , and N_g are the number of wind turbine, photovoltaic, and thermal units; Y is the planning horizon; K_g^{maint} is the maintenance coefficient of thermal unit g ; r^d is the discount rate; r^{maint} is the growth rate of the maintenance cost; C_{op}^{day} is the typical daily operating cost of the system; k is the effective service life of the unit.

The constraints of the upper-level planning model are shown in Equations (27)–(29).

(1) Capacity constraints for wind, photovoltaic, and thermal units

$$\begin{cases} c_{w,min} \leq N_{w1}P_w \leq c_{w,max} \\ c_{p,min} \leq N_{p1}P_p \leq c_{p,max} \\ c_{g,min} \leq N_gP_T \leq c_{g,max} \end{cases} \quad (27)$$

where $c_{w,min}$ and $c_{w,max}$ are the upper and lower limits of wind power installed capacity, respectively; $c_{p,max}$ and $c_{p,min}$ are the upper and lower limits of photovoltaic installed capacity, respectively; $c_{g,max}$ and $c_{g,min}$ are the upper and lower limits of thermal units installed capacity, respectively; P_p is the individual capacity of the photovoltaic.

(2) Generation capacity constraints of DC sending system

The equivalent power output of wind farms and photovoltaic plants are denoted as P_{w_e} and P_{p_e} , respectively.

$$\begin{cases} P_{w\_e,i} = k_{w\_e}P_{w\_total,i} = k_{w\_e}N_{w1}P_w \\ P_{p\_e,j} = k_{p\_e}P_{p\_total,j} = k_{p\_e}N_{p1}P_p \end{cases} \quad (28)$$

where k_{w_e} and k_{p_e} are the average output level of wind and photovoltaic power, respectively; P_{w_total} and P_{p_total} are the total installed capacity of wind farms and photovoltaic plants, respectively.

The DC-rated delivered power is P_{dN} . To meet the DC power demand, the generation capacity constraints of the DC sending system are shown in Equation (29).

$$\sum_{i=1}^{N_w} k_{w\_e}P_{w\_total,i} + \sum_{j=1}^{N_p} k_{p\_e}P_{p\_total,j} + N_g C_g \geq P_{dN} \quad (29)$$

5.3.2. Lower-Level Optimization Model

The lower-level optimization model considers the power balance constraint and operational constraints for wind–solar–thermal storage. The coordinated scheduling of multiple resources will meet the sending load demand and realize the minimum system operating cost. The comprehensive cost is composed of the operation cost of the thermal units and the abandonment penalty cost of renewable energy. The objective function is shown as Equations (30)–(33).

$$F = \min \left(\sum_{t=1}^{N_T} \sum_{g=1}^{N_g} C_{g,t} + \sum_{t=1}^{N_T} \sum_{g=1}^{N_g} C_{g,t}^{ud} + \sum_{t=1}^{N_T} C_{cur,t}^{dw} \right) \quad (30)$$

$$C_{g,t} = a_g P_{g,t}^2 + b_g P_{g,t} + c_g \quad (31)$$

$$C_{g,t}^{ud} = c_g^u s_{g,t}^u + c_g^d s_{g,t}^d \quad (32)$$

$$C_{cur,t}^w = \lambda \left(\sum_{i=1}^{N_w} P_{i,t}^{wpre} - P_t^{dw} + \sum_{j=1}^{N_p} P_{j,t}^{ppre} - P_t^{dp} \right) \quad (33)$$

where $C_{g,t}$ is the generation cost of thermal power unit g ; a_g, b_g, c_g are the generation cost coefficients; $P_{g,t}$ is the power output of unit i in period t ; $C_{g,t}^{ud}$ is the startup and shutdown cost of the thermal units; c_g^u, c_g^d are the startup and shutdown cost of thermal units, respectively; $s_{g,t}^u, s_{g,t}^d$ are the startup and shutdown state variable of unit g , respectively; $P_{i,t}^{wpre}$ and $P_{j,t}^{ppre}$ are the predicted power of wind farms and photovoltaic plants, respectively; P_t^{dw} and P_t^{dp} are the total dispatched power output of the wind stations and photovoltaic plants, respectively; λ is the penalty cost coefficient for renewable energy curtailment; N_T is the number of scheduling periods.

The operational constraints of the lower-level scheduling model are shown in Equations (34)–(50).

(1) Power balance constraints:

$$\sum_{g=1}^{N_g} P_{g,t} + P_t^{dw} + P_t^{dp} + P_t^s + P_t^{sup} = P_t^{HVDC} \quad (34)$$

where P_t^{HVDC} is the DC transmission power at period t ; P_t^s is the power output of the energy storage; P_t^{sup} is the support power from the AC power grid at period t .

(2) Power output constraints of wind, photovoltaic, and thermal units:

$$u_{g,t}P_{g,\min} \leq P_{g,t} \leq u_{g,t}P_{g,\max} \quad (35)$$

$$\begin{cases} 0 \leq P_t^{\text{dw}} \leq \sum_{i=1}^{N_w} P_{i,t}^{\text{wtpre}} \\ 0 \leq P_t^{\text{dp}} \leq \sum_{j=1}^{N_p} P_{j,t}^{\text{pvpre}} \end{cases} \quad (36)$$

where $P_{g,\max}$, $P_{g,\min}$ are the upper and lower limits of the active output of thermal unit g , respectively; $u_{g,t}$ is the operating state of thermal unit g at period t .

(3) Ramp capacity constraint of thermal units:

$$-R_i^{\text{dn}}\Delta T \leq P_{i,t} - P_{i,t-1} \leq R_i^{\text{up}}\Delta T \quad (37)$$

where R_g^{up} , R_g^{dn} are the upward and downward ramping rates of unit g , respectively; ΔT is the scheduling time interval.

(4) Reserve capacity constraint of thermal units:

$$\begin{cases} \min(P_{g,\max} - P_{g,t}, R_g^{\text{up}}\Delta T) \geq r_{g,t}^{\text{ur}} \\ \min(P_{g,t} - P_{g,\min}, R_g^{\text{dn}}\Delta T) \geq r_{g,t}^{\text{dr}} \end{cases} \quad (38)$$

where $r_{g,t}^{\text{ur}}$ and $r_{g,t}^{\text{dr}}$ are the upward and downward reserve capacity of thermal unit g , respectively.

(5) Energy storage operation constraints

Constraint (39) depicts the state of charge in the energy storage. Constraint (40) limits the stored electricity in the energy storage. The energy storage capacity in the final period is ensured by constraint (41).

$$E_{s,t+1} = E_{s,t} + \eta_c P_t^{\text{s,c}} - P_t^{\text{s,d}} / \eta_d \quad (39)$$

$$E_{\min}^s \leq E_{s,t} \leq E_{\max}^s \quad (40)$$

$$E_{s,0} = E_{s,N_T} \quad (41)$$

where $E_{s,t}$ is the state of charge in the energy storage; $E_{\min}^s$ and $E_{\max}^s$ are the lower and upper limit of electricity energy storage, respectively; η_c and η_d are the charging and discharging efficiency of the energy storage, respectively.

The charge and discharge power of energy storage is limited by constraint (42).

$$\begin{cases} 0 \leq P_t^{\text{s,c}} \leq u_t^{\text{s,c}} P_{\max}^{\text{s,c}} \\ 0 \leq P_t^{\text{s,d}} \leq u_t^{\text{s,d}} P_{\max}^{\text{s,d}} \\ P_t^{\text{s}} = P_t^{\text{s,d}} - P_t^{\text{s,c}} \end{cases} \quad (42)$$

where $u_t^{\text{s,c}}$ and $u_t^{\text{s,d}}$ are the charging and discharging state variables of the energy storage; $P_{\max}^{\text{s,c}}$ and $P_{\max}^{\text{s,d}}$ are the maximum charging and discharging power of the energy storage, respectively.

Constraint (43) depicts the operational state limit of energy storage.

$$u_t^{\text{s,c}} + u_t^{\text{s,d}} \leq 1 \quad (43)$$

The upward and downward reserve capacities of energy storage are limited by constraints (44) and (45).

$$0 \leq r_{s,t}^{\text{u,ES}} \leq \eta_d (E_{s,t} - E_{s,t-1}) - P_t^{\text{s,d}} \quad (44)$$

$$0 \leq r_{s,t}^{d,ES} \leq (E_{s,t-1} - E_{s,t})/\eta_c - P_t^{s,c} \quad (45)$$

where $r_{s,t}^{u,ES}$ and $r_{s,t}^{d,ES}$ are the upward and downward reserve capacity provided by the energy storage, respectively.

(6) System reserve capacity constraints:

$$\begin{cases} \sum_{g=1}^{N_g} r_{g,t}^{ur} + r_{s,t}^{u,ES} \geq r_t^{up} \\ \sum_{g=1}^{N_g} r_{g,t}^{dr} + r_{s,t}^{d,ES} \geq r_t^{dn} \end{cases} \quad (46)$$

where r_t^{up}, r_t^{dn} are the upward and downward reserve capacity requirements of the system at period t , respectively.

(7) Grid support power constraints:

The support power from the AC power grid is limited by constraints (47) and (48).

$$-\zeta P_t^{HVDc} \leq P_t^{Sup} \leq \zeta P_t^{HVDc} \quad (47)$$

$$\sum_{t=1}^{N_T} P_t^{Sup} = 0 \quad (48)$$

where ζ is the grid support coefficient.

(8) Proportion constraints of renewable energy:

$$\frac{\sum_{t=1}^{N_T} (P_t^{dw} + P_t^{dp})}{\sum_{t=1}^{N_T} P_t^{HVDc}} \geq \delta \quad (49)$$

where δ is the requirement for the proportion of renewable energy.

(9) Curtailment rate constraints of renewable energy:

$$\begin{cases} \sum_{t=1}^{N_T} P_t^{wt} \geq (1 - \mu) P_t^{wtpre} \\ \sum_{t=1}^{N_T} P_t^{pv} \geq (1 - \mu) P_t^{pvpre} \end{cases} \quad (50)$$

where μ is the curtailment rate limit of renewable energy.

6. Simulation Results and Discussion

To verify the validity of the proposed model, an 8000 MW DC sending system of the Northwest Grid of China is taken as an example for simulation analysis. The supporting thermal power unit is the 660 MW unit, and the minimum output is taken as 30% of the installed capacity, which is obtained from the actual HVDC transmission engineering of Xinjiang, China. The investment cost of the individual unit is 4.4×10^6 CNY/MW. The investment cost of the wind turbine is taken as 4×10^6 CNY/MW, and the capacity of a single turbine is 2 MW. The investment cost of photovoltaic is taken as 3.5×10^6 CNY/MW. The investment cost of energy storage capacity is taken as 1.5×10^6 CNY/MW, and the investment cost of energy storage power is taken as 6×10^5 CNY/MW. The cost coefficients of multiple generation resources are obtained from reference [33,34]. The minimum penetration rate of renewable energy in the sending system is taken as 30%. The discount rate for the planning year is 8%. The planning period and design life of the thermal power unit are both 25 years, and the design life of the energy storage is taken as

15 years. Typical power demand curves and typical scenarios for wind and photovoltaics are shown in Figures 4–6. The final renewable energy power scenarios are obtained by combining wind power and photovoltaic scenarios, with a quantity of 48. The data on renewable energy and delivery load are obtained from the actual HVDC system of Xinjiang, China. The MATLAB 2016b (The MathWorks, Natick, MA, USA) is utilized to process and analyze the results of experimental studies. The proposed models are solved by GUROBI 11.0.1 (Gurobi Optimization, Beaverton, OR, USA).

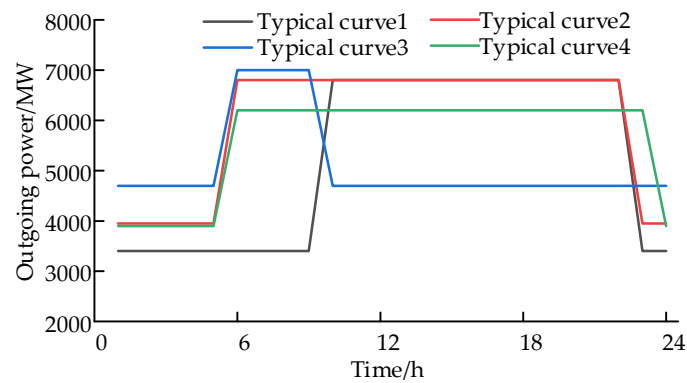


Figure 4. Typical curves of the sending load demand.

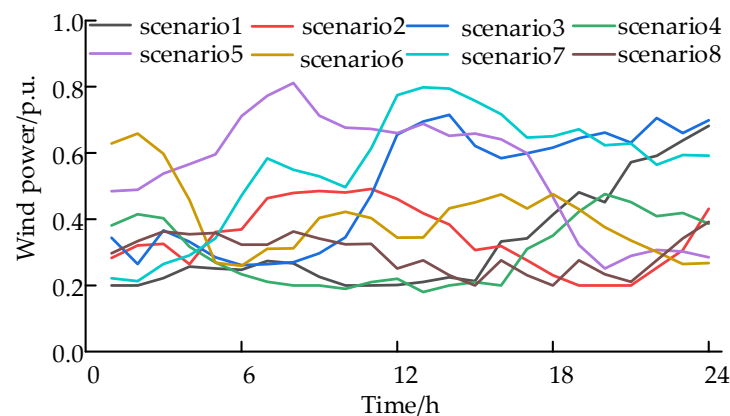


Figure 5. Typical scenarios of wind power output.

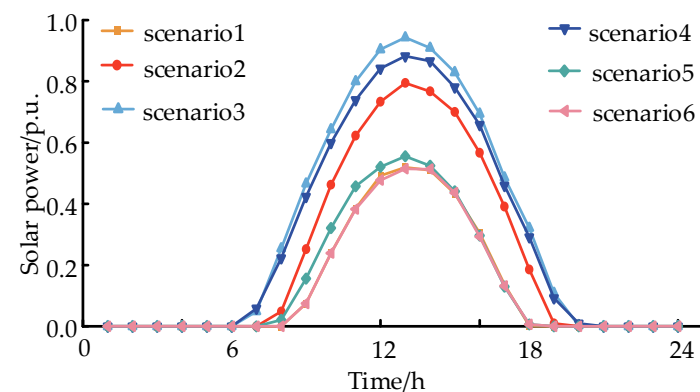


Figure 6. Typical scenarios of solar power output.

6.1. Analysis of the Results of the Planning of Wind–Photovoltaic–Thermal Storage Capacity

To verify the effectiveness of the proposed planning method, two planning schemes are set up for comparative analysis. Scheme 1: wind–photovoltaic–thermal-storage DC sending transmission system planning scheme without considering transient overvoltage

constraints. Scheme 2: wind–photovoltaic–thermal-storage DC sending transmission system planning scheme considering transient overvoltage constraints. The grid support coefficient is set to 0 (i.e., the grid support is not considered). The planning results of the two schemes are shown in Table 1.

Table 1. Optimization results for different planning schemes.

Configuration Schemes	Thermal Unit/MW	Wind/MW	Solar/MW	Energy Storage Power/MW	Energy Storage Capacity/MWh	Investment Cost/ 10^9 CNY
Scheme 1	4620	6692	5489	846	3825	630.99
Scheme 2	5280	7974	6386	1245	6047	738.11

As shown in Table 1, to guarantee sufficient short-circuit capacity and reduce the transient overvoltage in case of DC faults, compared with Scheme 1, the total installed capacity of new energy power sources of Scheme 2 is increased by 17.89%. Compared with Scheme 1, the installed capacity of wind farms and photovoltaic power of Scheme 2 is increased by 1282 MW and 897 MW respectively, and the total cost of investment is increased by CNY 10.712 billion. As shown in Figure 7, in the event of a bipolar blocking fault in the DC sending system, the transient overvoltage of Scheme 2 is low, and the transient overvoltage amplitude is 1.300 p.u., which is 8.25% lower than that of Scheme 1. Therefore, Scheme 2 can effectively reduce the level of transient overvoltage after a DC fault and guarantee the safety of the system operation. Scheme 2 can reduce the risk of renewable energy disconnection and guarantee the security of the system at the expense of a certain economy.

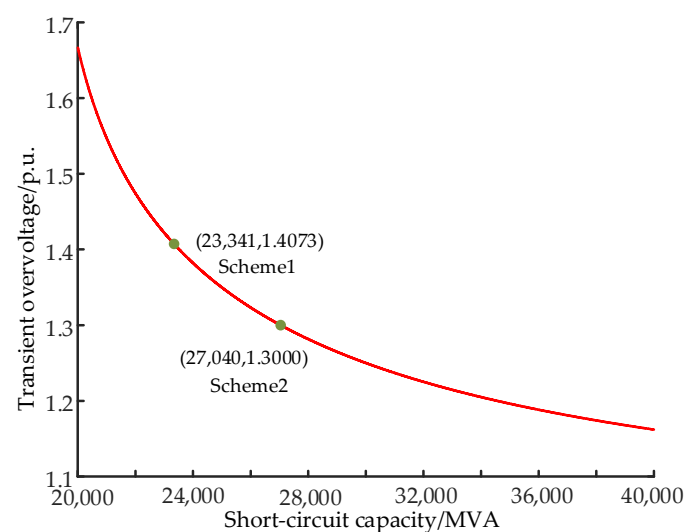


Figure 7. Transient overvoltage case under DC system faults.

In terms of the penetration and consumption of renewable energy, although the economy of Scheme 2 is inferior to that of Scheme 1, the proportion of renewable energy (i.e., renewable energy penetration) is 53.86%, and the abandonment rate of renewable energy is 32.96%, which is 8.46% and 2.96% more than that of Scheme 1, respectively. Therefore, Scheme 2 can effectively enhance the proportion of renewable energy in the sending electricity and guarantee the efficient send-out and inter-regional sharing of renewable energy. The power and capacity of energy storage in Scheme 2 are 1245 MW and 6047 MWh. The energy storage duration is 4.85 h. Compared with Scheme 1, the power and capacity of energy storage in Scheme 2 are increased by 399 MW and 2222 MWh, respectively. A

larger energy storage capacity can effectively improve the sending transmission system operational flexibility and broaden the consumption space for renewable energy.

Therefore, to ensure system operation security, the proposed planning method (Scheme 2) configures more generation resources and energy storage capacity. Though the overall economy reduces, the penetration of renewable energy significantly improves. The proposed planning method can guide the gradual improvement of the proportion of renewable energy in the DC sending system.

Based on the consideration of actual engineering, the impact of the wind-and-light ratio on the planning scheme is considered. The thermal power installed capacity is fixed, and the optimization configuration results under the different wind and photovoltaic ratios are shown in Table 2.

Table 2. Configuration results of wind–photovoltaic–thermal storage under different wind and photovoltaic ratios.

Wind and Photovoltaic Ratios	Wind/MW	Solar/MW	Energy Storage Power/MW	Energy Storage Capacity/MWh	Annual Average Cost/10 ⁹ CNY
3:1	10,092	3364	2961	14,805	138.31
2:1	9220	4610	1917	9589	132.00
1.5:1	8486	5657	1640	8202	131.99
1.25:1	7978	6382	1244	6066	129.96
1:1	7322	7322	1375	6621	133.16
4:5	6638	8297	1405	7027	136.09
1:2	5186	10,372	1927	7945	138.06
1:3	4934	14,802	3216	8870	160.79

As can be seen from Table 2, compared with the configuration results of Scheme 2, an excessive increase and decrease in the proportion of photovoltaics will increase the system storage configuration power and capacity and average annual operating costs. When the wind and photovoltaic ratio is close to 1.25:1, it will help to utilize the complementary characteristics of wind power and photovoltaic power and optimize the allocation of resources.

6.2. Comparative Analysis of the Operating Results of Different Planning Schemes

For the different configuration schemes, typical days are selected for simulation analysis, and transient overvoltage constraints are considered in the operation model. The results are shown in Figures 8–11. From Figures 8 and 9, it can be seen that both planning schemes can meet the power demand of the DC sending system during the daily dispatch operation and deliver power to the interconnected grid according to the power plan. In Scheme 2, to ensure adherence to the transient overvoltage constraint and maintain the transient voltage rise control within the safety range, the start-up capacity of the thermal units increases, which makes the thermal power generation cost increase by 9.6% compared with Scheme 1. The renewable energy penetration is 63.37%, which can ensure a better proportion of green power for sending transmission. The transient overvoltage and short-circuit ratios of different schemes are shown in Figures 10 and 11. From Figure 9, it can be seen that Scheme 2 can satisfy the transient overvoltage constraint of 1.3 p.u. in all periods of the operation day. Scheme 2 can guarantee the operational safety of the DC sending system and reduce the risk of off-grid accidents of renewable energy in the nearby area. Compared with Scheme 2, Scheme 1 does not consider the transient overvoltage constraint in the planning process, and the short-circuit capacity is small in some hours, which cannot satisfy the transient overvoltage constraint. In these periods, relaxation processing is necessary to obtain a feasible solution, so that the transient voltage rise exceeds the threshold value of 1.3 p.u. during 12:00–14:00. When the sending power is

relatively higher, it is difficult to ensure the operational safety of the sending system in the case of a DC fault.

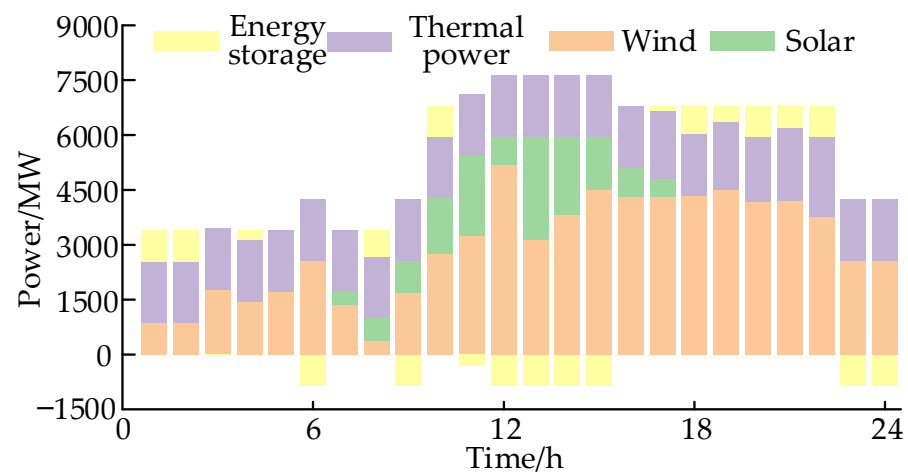


Figure 8. Operation results of Scheme 1 planning result.

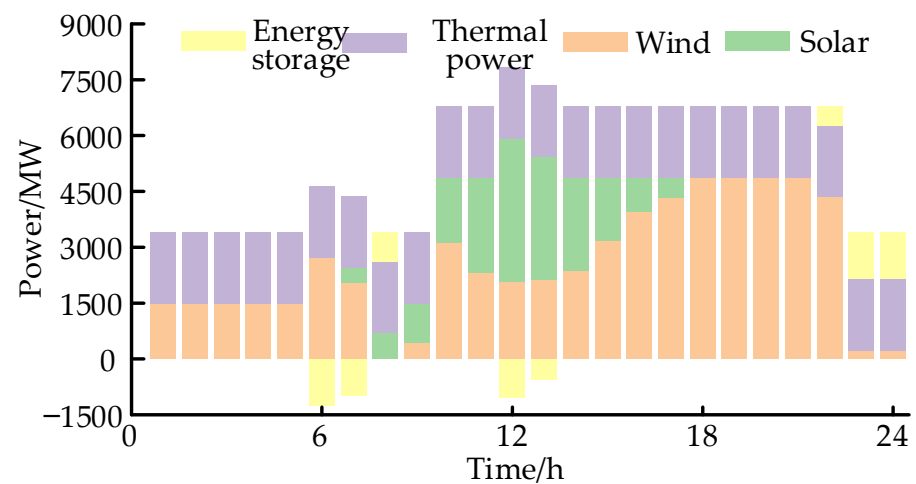


Figure 9. Operation results of Scheme 2 planning result.

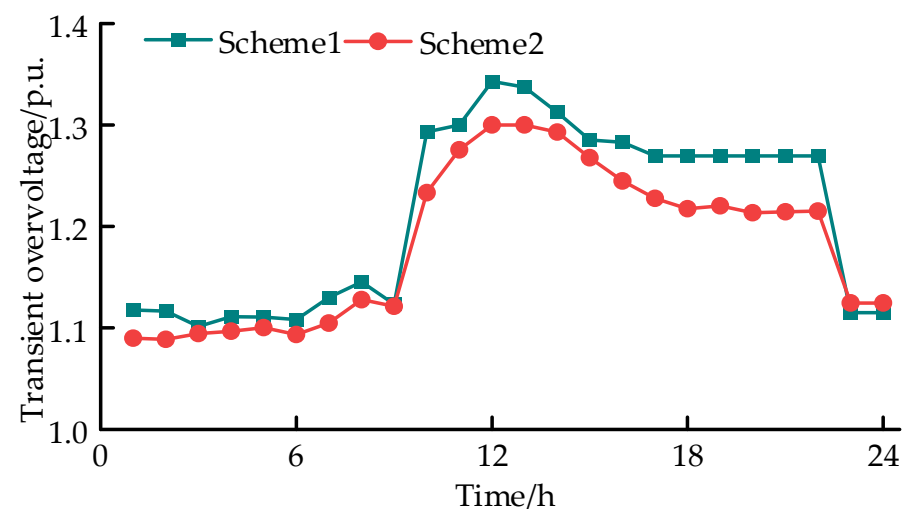


Figure 10. Transient overvoltage conditions of different schemes under DC faults.

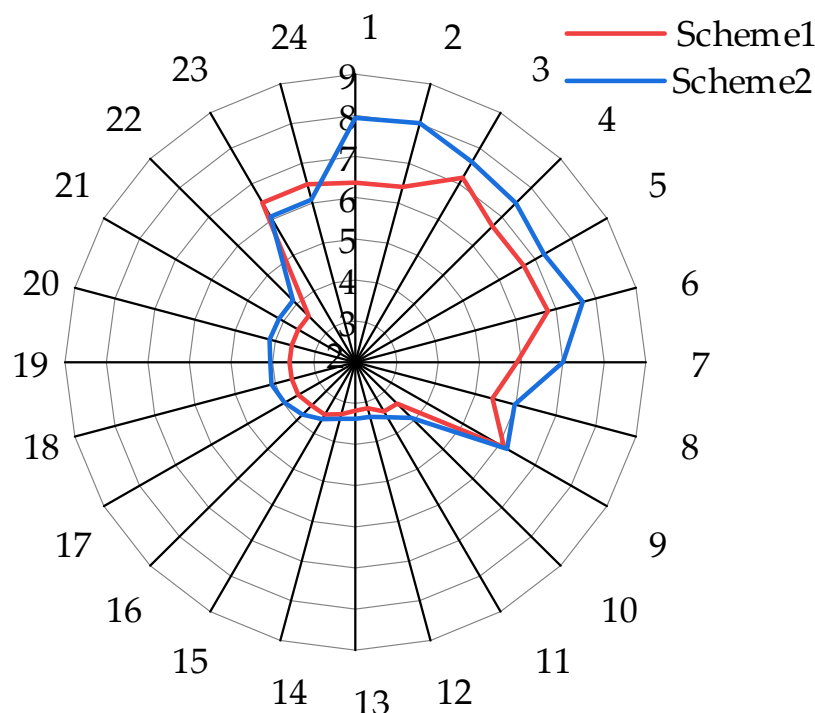


Figure 11. Comparison of short-circuit ratio results for different planning schemes.

From Figure 11, it can be seen that both Scheme 1 and 2 have a high short-circuit ratio in the 1:00–9:00. This is because the sending-out load is at a low level during these periods, and the HVDC converter consumes less reactive power. The short-circuit capacity provided by wind power and thermal power can ensure a high short-circuit ratio for the HVDC transmission system. Therefore, the transient voltage stability is enhanced, and the risk of new energy disconnection is low. However, from 10:00 to 22:00, the system short-circuit ratio decreases, and the transient overvoltage is at a high level. This is because the delivery load of the external transmission system significantly increases, and the reactive power consumption of the converter also rises. On the other hand, compared to Scheme 1, Scheme 2 can maintain a high short-circuit ratio level and keep the transient overvoltage within a safe range while completing the external transmission plan.

6.3. Impact Analysis of Grid Support Power

The planning results for wind–photovoltaic–thermal storage under different grid support capacities are shown in Table 3. As shown in Table 3, with the gradual increase in the grid support level, the energy storage capacity of the DC sending system gradually decreases, while the average annual operating cost of the outgoing system also decreases. By increasing the coordination with the sending AC power system, the renewable energy consumption space of the integrated sending system can be enhanced, and the investment and operating cost of the supporting resources can be reduced. Meanwhile, the economy and efficiency of the planning and operation can be improved.

Table 3. Configuration results under different grid support power levels.

Grid Support Power	Wind/MW	Solar/MW	Energy Storage Power/MW	Energy Storage Capacity/MWh	Annual Average Cost/10 ⁹ CNY
0	7974	6386	1245	6047	129.95
2.5%	8242	6003	1140	5001	127.93
5%	8510	5620	1045	4157	126.04
10%	8828	4166	921	3243	122.97

7. Conclusions

This article proposes the capacity planning method for wind–solar–thermal-storage bundled HVDC sending systems considering transient overvoltage constraints. The quantile regression analysis and Gaussian mixture modeling are utilized to generate the stochastic scenario set to describe the uncertainty of renewable energy. The transient overvoltage and influencing factors of the integrated DC transmission system are analyzed. The relationship between the output of thermal units and renewable energy at the sending end and the system short-circuit capacity is derived. The transient overvoltage constraint corresponding to the voltage support strength is constructed. The double-layer capacity planning model of the wind–solar–thermal-storage bundled HVDC sending system is established. The optimal capacity planning scheme for the wind–solar–thermal storage is determined through the coordinated optimization of the two-layer model. The feasibility of the method proposed in this paper was verified through case studies. The results show that the proposed planning method can reduce the risk of renewable energy disconnection and guarantee the security of the system at the expense of a certain economy. Meanwhile, the established planning model can maintain a higher short-circuit ratio and improve the voltage support strength under the premise of completing the sending plan. The transient overvoltage can be maintained in the safe range.

This paper focuses on the planning method for a wind–solar–thermal-storage bundled HVDC sending system. However, this study can be improved further, and future research can be conducted from the following aspects:

- (1) Machine learning methods based on the use of artificial neural networks could be investigated and utilized to obtain the most reliable short-term and long-term generation scenarios for renewable energy;
- (2) The control strategies of the HVDC transmission line and multiple generation resources could be added to comprehensively investigate the static and dynamic stability in the planning methods;
- (3) The optimization objective in this study focuses on investment costs and operating costs. In the future, the electricity sales revenue and the benefits of participating in the auxiliary service markets could be further considered to optimize the HVDC system's life-cycle economy.

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