Optimal Scheduling of Pumped Storage in Power System with Large-scale Photovoltaic Based on Carbon Emissions Trading

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Abstract. In order to improve the photovoltaic penetration of the power system, an optimal scheduling model of pumped storage system with large-scale photovoltaic based on carbon trading is proposed in this paper. Firstly, based on the analysis of low-carbon economy, the stepped carbon emission trading mechanism is introduced into the economic dispatch of power system. And in order to improve the calculating efficiency, an improved K-means clustering algorithm based on maximum and minimum distance criterion is proposed to cluster the photovoltaic power generation scenarios. Then the optimal scheduling model is established. Take the lowest comprehensive operation costs of the system as the objective function, and the operation economy and low carbon of the system are considered. The pumped storage is used as energy storage for peak load shaving in the generation system. At last, an improved IEEE RTS-96 system is taken to finish the case study, and the simulation results show that the model proposed in this paper is reasonable and effective.

1. Introduction
Recently, the development of wind power and photovoltaic power generation is rapid. Since the wind power and photovoltaic power generation are greatly affected by the weather, the output has extreme randomness and uncertainty. Particularly, photovoltaic power generation is completely affected by weather factors. Thus, with the penetration of photovoltaic power generation increases, it will have great impact on the safe and stable operation of the power system [1].

As a type of mature energy storage, pumped storage has the advantages of large regulating capacity and high energy utilization efficiency [2]. Thus, it is very suitable for peak load shaving which can improve the penetration of photovoltaic power generation.

Meanwhile, in order to achieve the low-carbon economic dispatch of power system, low-carbon economy is introduced into the economic dispatching of power system [3], which can achieve the two goals of economic operation and low-carbon environmental protection of power system at the same time. In [4], both the economy of power system operation and the low carbon emission of the system are considered in large-scale wind power system, and in [5] an economic dispatching model of power system is established, which improves the utilization rate of wind power. In [6], the economic dispatching model of power system with large-scale photovoltaic power system is studied, and the low-carbon emission economy of the system is taken into account, but the participation of energy storage in power system operation is not considered. In [7], the economic dispatching model is modified, but the energy storage system is not included in the model.
In view of this, an optimal scheduling model for pumped storage in large-scale photovoltaic power system based on carbon trading is proposed in this paper. By fulling use of the large regulating capacity advantage of pumped storage units, it can be used for peak load shaving operation of the system to improve the penetration and utilization efficiency of photovoltaic, and by considering about the carbon trading emissions to achieve the purpose of low-carbon economic dispatch of the system.

2. The introduction and analysis of carbon trading mechanism and its impact
At present, as an environmental protection implementation mechanism, the low-carbon economy is a better way to achieve low energy consumption, low pollution and low emissions. Therefore, in order to achieve the goal of energy saving and emission reduction, the carbon trading mechanism is mostly introduced in current research.

2.1. The introduction of carbon trading mechanism
Now there are two main carbon trading markets in the world, which are quota-based carbon trading market and project-based carbon trading market. And according to the current situation and development trend of China's economic development, it mainly participates in the project-based carbon emissions trading market, namely the clean development mechanism market (CDM).

In the project-based market trading mechanism, the carbon emissions allocated to each economic entity in advance are used as the benchmark, and the actual carbon emissions of each economic entity are monitored in real time. If the actual carbon emission of the economic entity is lower than the given standard in a certain time period, it can obtain additional carbon emission credit quota and trade it. On the contrary, the economic entity needs to pay a certain fee for corresponding carbon emission credit quota [8].

2.2. The carbon emission costs and the benefit analysis
The introduction of carbon trading mechanism has a great impact on the overall operation costs of power system. When the carbon emission quotas are not exceeded, the operating costs of the system can be reduced by selling the remaining quota. When the carbon emission quota is insufficient, the operating cost of the system can be increased by purchasing the excess carbon emission quota and paying the corresponding excess penalty fee.

In order to develop key projects in the field of CDM in China more accurately, an allocation model of carbon emissions trading quota in power system based on the "China Regional Power Grid Baseline Emission Factor 2013" is proposed in this paper, which is shown in (1):

$$Y_{C,i} = \sum_{i=1}^{N} \varepsilon P_{i,t} \Delta t$$  \hspace{1cm} (1)

where, $Y_{C,i}$ is the carbon emission trading quota; $N$ is the total number of generating units, $P_{i,t}$ is the generation output of the first generating unit in the $t$th time interval, $\varepsilon$ is the allocation coefficient of the carbon emission quota per unit of electrical energy of the generating unit, $\Delta t$ is the time interval according to the different research questions, the value of 1 is chosen in this paper.

The corresponding carbon emission trading quota in the optimal operation of the power system carbon emissions trading costs are described in detail in Chapter III below.

3. Photovoltaic output scene clustering method based on improved K-mean algorithm
Because of the extremely high randomness and uncertainty of photovoltaic power generation, its power generation is completely affected by the weather, and in the actual power system optimal dispatch, it is impossible to analyze every photovoltaic power generation scenario. Therefore, some clustering analysis methods are usually used to obtain the typical photovoltaic output scenarios for analysis.
The commonly used clustering analysis methods are K-means clustering method and clustering algorithm based on KD distance. In this paper, the K-means clustering method is introduced and it is improved to obtain more typical photovoltaic output scenarios and their probabilities.

3.1. The principle of K-means clustering method
The principle of K-means clustering method is to divide m vectors \( y_i \) into n groups, which is based on minimizing the sum of the Euclidean distances between the vectors of each group and the clustering centers of the group, as is shown in (2):

\[
\text{Dis} = \sum_{n=1}^{N} \left( \sum_{i \in Q_n} \left\| y_i - p_c \right\|^2 \right)
\]

where Dis represents the sum of the distance of each group of vectors and the Euclidean distance of the clustering center, \( y_i \) is the \( i \)th vector, \( p_c \) is the \( c \)th clustering center, \( N \) is the number of clustering groups; \( Q_c \) is the \( c \)th clustering vector group.

3.2. An improved K-means clustering method
In this paper, in order to put forward the idea based on the maximum and minimum distance criterion, the K-means clustering algorithm is improved accordingly. The clustering effect is measured by intra-group and inter-group difference measures, as is shown in (3) and (4). Where, \( t \) represents difference measure index value within the group and \( T \) represents the difference measure index value between groups. Among them, the clustering effect is better if the difference measure index value between objects within the group is smaller and the difference measure index value of cluster center between groups is larger:

\[
t = \sum_{m=1}^{M} \sum_{i \in Q_m} \left\| y_i - p_c \right\|
\]

\[
T = \sum_{1 \leq i,j \leq M} \left\| p_i - p_j \right\|
\]

where \( y \) is the object in \( Q_c \); \( p_i \) and \( p_c \) are the clustering centers of \( G_i \) and \( G_c \) respectively.

Taking the historical power output data of a photovoltaic power station in Hainan as an example, the commonly used K-means clustering method and the improved K-means clustering method proposed in this paper are compared. And the two indicators are shown in Table 1. It can be seen that the improved K-means clustering algorithm has smaller difference measure index values among objects in the group, and it has larger difference measure index values among cluster centers. Thus, it has a better clustering effect than the algorithm before improved.

| Clustering Algorithm               | \( t \)  | \( T \)  |
|-----------------------------------|---------|---------|
| K Means Clustering Algorithm      | 1052    | 1598    |
| Modified K Means Clustering Algorithm | 858    | 1254    |

4. The Optimal Dispatching Model of Pumped Storage Energy Based on Carbon Trading

4.1. The principle of the model
Considering the great uncertainty and power output fluctuation of photovoltaic electricity sources, an optimal scheduling model of pumped storage in large-scale photovoltaic power system based on carbon trading which aims to reduce its impact on power system operation is proposed in this paper.
When the photovoltaic power output is integrated into the power grid, the pumped storage units are used for peak load and power surplus shaving in the power system. Thus, through the coordinated operation of pumped storage system in the photovoltaic generation system, the whole system can achieve the optimum low-carbon economic operation state. The optimal dispatching model is shown in Figure 1.

**Figure 1.** The schematic diagram of a pumped storage scheme in a power system with high penetration of PV

In the figure, $P_G$ represents the power output of thermal power units, $P_V$ represents the power output of photovoltaic power stations, $P_H$ represents the power output of pumped storage units, $P_L$ is the load value of the system, $P_{NL}$ is the net load value of the system.

### 4.2. Calculating the cost of carbon transaction

If the total carbon emissions in a certain time period in the system are determined to be $Y_{c,t}$, then the carbon trading cost $F_{C,t}$ can be calculated as shown in (5)–(7).

$$F_{C,t} = \begin{cases} K_{CDM}\Delta Y_{CDM,t} + K_p\Delta Y_{P,t} & \Delta Y_{t} > 0 \\ K_{CDM}\Delta Y_{CDM,t}^' & \Delta Y_{t} \leq 0 \end{cases}$$  \hspace{1cm} (5)

$$\Delta Y_{t} = Y_{c,t} - Y_{D,t}$$  \hspace{1cm} (6)

$$Y_{c,t} = \sum_{i=1}^{N_G} \left( a_i P_{Gi,t}^2 + b_i P_{Gi,t} + c_i \right)$$  \hspace{1cm} (7)

where $N_G$ is the total number of thermal power units in the system, $Y_{CDM}$ represents the unit transaction price, $K_p$ represents the penalty coefficient of the carbon trading emissions exceeding the portion payable, $\Delta Y_{CDM,t}$ represents the amount of emissions obtained through CDM exchanges in $t$th period, $\Delta Y_{P,t}$ represents the additional amount of carbon emissions obtained through the payment of fines in $t$th period, $\Delta Y_{CDM,t}^'$ represents the carbon emission quotas sold on the market through CDM trading in the $t$th period, $\Delta Y_t$ represents the difference between total carbon emissions $Y_{c,t}$ and the allocated emission quota $Y_{D,t}$, $P_{Gi,t}$ is the power output of the $i$th thermal power unit in $t$th period, $a_i$, $b_i$, $c_i$ are the emission coefficients of the $i$th thermal power unit respectively.

### 4.3. Objective function

Based on the analysis of photovoltaic power output characteristics, the objective function of this model is to obtain the lowest expected operating costs of all the clustered scenarios. The calculation formula is as follows:
\[
\begin{align*}
\min F &= \min \left( F_G + F_{PV} + F_{LOSS} + F_C \right) \\
\text{where, } F_G &\text{ represents the electricity generating costs of power generation, } F_{PV} \text{ represents the penalty costs of abandon photovoltaic in the system, } F_{LOSS} \text{ represents the penalty costs of insufficient power supply in the system, } F_C \text{ represents the carbon emission transaction costs in the system.}
\end{align*}
\]

1) Electricity generating costs of power generation

\[
F_G = \sum_{l=1}^{N_l} p_l \cdot F_{G,l}
\]

\[
F_{G,l} = \sum_{i=1}^{N_G} \sum_{t=1}^{T} v_{i,l,t} \left( a_i P_{G,i,t,l}^2 + b_i P_{G,i,t,l} + c_i \right)
\]

where \( p_l \) represents the probability of the \( l \)th photovoltaic scene, \( N_l \) represents the total number of photovoltaic scenes, \( F_{G,l} \) represents the power consumption costs of the \( l \)th photovoltaic scene, \( v_{i,l,t} \) represents the start-up and shutdown state of the \( i \)th thermal power unit in the \( l \)th scenario, \( P_{G,i,t,l} \) represents the power output of the \( i \)th thermal power unit in the \( l \)th scenario in the \( t \)th period.

2) Penalty costs of abandoned photovoltaic generation

In the current power system operation, there doesn’t exist penalty costs of abandoned photovoltaic generation. However, in order to improve the penetration and utilization efficiency of photovoltaics, the penalty costs of abandoned photovoltaic generation is introduced to measure the utilization of photovoltaic in the model. The expressions of the penalty costs of abandoned photovoltaic generation are as follows.

\[
F_{PV} = \sum_{l=1}^{N_l} p_l \cdot F_{PV,l}
\]

\[
F_{PV,l} = \sum_{t=1}^{T} k_{PV} \cdot E_{PV,l,t}
\]

where \( F_{PV,l} \) represents the penalty costs of abandoned photovoltaic generation in the \( l \)th photovoltaic scene, \( k_{PV} \) represents the penalty costs of abandoned photovoltaic generation, \( E_{PV,l,t} \) represents the capacity value of abandoned photovoltaic generation.

3) Penalty costs of insufficient power supply

The penalty costs mainly consider the time that there is insufficient power supply, which will cause power cut. Thus, the penalty costs should be paid. The expression of penalty costs of insufficient power supply is as follows:

\[
F_{LOSS} = \sum_{l=1}^{N_l} p_l \cdot F_{LOSS,l}
\]

\[
F_{LOSS,l} = \sum_{t=1}^{T} k_{LOSS} \cdot F_{LOSS,l,t}
\]

where, \( F_{LOSS,l} \) represents the penalty costs of loss of load in the \( l \)th photovoltaic scene, \( k_{PV} \) represents coefficient of the penalty costs per unit loss of load, \( E_{LOSS,l,t} \) represents the capacity value of loss of load.

4) Transaction costs of carbon emissions

Based on the transaction costs of carbon emissions above, the expression is as shown below.

\[
F_C = \sum_{l=1}^{N_l} p_l \cdot F_{C,l}
\]
\[ F_{C,l} = \sum_{j=1}^{T} F_{C,l,t} \]  

where \( F_{C,l} \) represents the transaction cost of carbon emissions in the \( l \)th photovoltaic scenario, \( F_{C,l,t} \) represents the transaction cost of carbon emissions in the \( t \)th period in the \( l \)th photovoltaic scenario.

### 4.4. Constraints

The constraints of the model include power balance constraints and pumped storage operation constraints.

1) **The constraints of system power balance**

\[ \sum_{j=1}^{N_H} P_{H,j,l,t} + \sum_{j=1}^{N_H} \left( P_{H,j,l,t}^c + P_{H,j,l,t}^d \right) + P_{PV,l,t} = P_{L,t} \]  

where \( N_H \) represents the number of pumped storage units, \( P_{H,j,l,t}^c \) represents the pumping output of the \( j \)th pumped storage unit in the \( t \)th period of the \( l \)th photovoltaic scene, \( P_{H,j,l,t}^d \) represents the output of the \( j \)th pumped storage unit in the \( t \)th period of the \( l \)th photovoltaic scene, \( P_{PV,l,t} \) represents the output value of the \( t \)th period of the \( l \)th photovoltaic scene, and \( P_{L,t} \) represents the load value of the \( t \)th period.

2) **The constraints of pumped storage units operation**

\[ P_{H,j,l,t}^d = \mu_{j,l,t}^d \cdot P_{H,j} \]  

\[ 0 \leq P_{H,j,l,t}^c \leq \mu_{j,l,t}^c \cdot P_{H,j} \]

where, \( P_{H,j} \) represents the rated capacity of the \( j \)th pumped storage unit, \( \mu_{j,l,t}^c \) represents the pumping variable, the value 1 represents pumping state, \( \mu_{j,l,t}^d \) represents the generating variable, value 1 represents generating state.

3) **The constraints of reserve capacity in the power system**

In the reserve capacity constraints of the system, the balance between pumped storage units and photovoltaic power generation is not considered. The expression of the reserve capacity of the system is as follows.

\[ \sum_{j=1}^{N_H} P_{G,j,l,t} u_{i,l,t} - P_{L,t} \geq R_i \]  

where, \( P_{G,j} \) represents the rated capacity of the \( i \)th thermal power unit, \( u_{i,l,t} \) represents the start-up variable of the thermal power unit, and the value of 1 represents the start-up state, \( R_i \) represents the reserve capacity of the system at \( t \)th period.

4) **The constraints of energy storage capacity of pumped storage system**

\[ E_{H,j,l} \leq E_{\text{max}} \]

where, \( E_{H,j,l} \) represents the \( j \)th energy capacity pumped storage unit at \( t \)th period, \( E_{\text{max}} \) represents the maximum capacity of pumped storage.

### 5. Case Study

The case study is carried out based on the IEEE RTS-96 system. The specific unit parameters and load data can be found in [9]. The capacity of photovoltaic power station in the system is 840 MW, and the penetration of photovoltaic is 30%. The rated capacity of a single pumped storage unit in the system is 150 MW, and the comprehensive efficiency of pumping and power generation cycle is 81%.

The transaction cost price of carbon emissions can be found in [10], and the transaction price of greenhouse gases is 320 RMB per ton.
The model is solved by calling CPLEX in the Matlab platform, which is the commercial optimization software.

5.1. Optimal scheduling of pumped storage system
After finishing the optimization dispatch analysis and calculation, two pumped storage units (2×150MW) allocated in the system can minimise generation costs in the power system. The detail of operation status of the pumped storage units obtained by optimization is shown in Figure 2.

![Figure 2. Operation of Pumped Storage Units in Photovoltaic Grid-connected Power System](image)

The pumped storage units generate electricity at peak load periods, and pump and stores electricity at night and afternoon when the load is low, which improve the operation economy of the system.

The economic situation of the power system before and after the installation of pumped storage units is compared and analyzed, as shown in Table 2. It can be seen that the operation economy of the system has been significantly improved after the configuration of pumped storage units.

| without pumped storage units | $F_G$ | $F_{PV}$ | $F_{LOSS}$ | $F_C$ | $F$ |
|-----------------------------|-------|---------|------------|-------|-----|
| 2.42×10^6                  | 6.1×10^4 | 2.3×10^2 | 3.6×10^2 | 2.481×10^6 |
| with pumped storage units   | 2.13×10^6 | 5.2×10^4 | 2.1×10^2 | 3.1×10^2 | 2.182×10^6 |

5.2. Optimal scheduling results with different penetration of PV
In order to verify the applicability of the model, the optimal results with different penetration of PV are shown in Table 3.

| penetration of PV | $F_G$ | $F_{PV}$ | $F_{LOSS}$ | $F_C$ | $F$ |
|------------------|-------|---------|------------|-------|-----|
| 10               | 2.51×10^6 | 4.3×10^4 | 1.7×10^2 | 6.3×10^2 | 2.554×10^6 |
| 20               | 2.22×10^6 | 4.9×10^4 | 1.8×10^2 | 4.9×10^2 | 2.270×10^6 |
| 30               | 2.13×10^6 | 5.2×10^4 | 2.1×10^2 | 3.1×10^2 | 2.182×10^6 |
| 35               | 2.01×10^6 | 5.7×10^4 | 2.3×10^2 | 2.6×10^2 | 2.067×10^6 |
| 40               | 1.96×10^6 | 6.3×10^4 | 2.7×10^2 | 2.4×10^2 | 2.024×10^6 |
From Table 3, when the penetration of PV increases, the electricity generating costs and transaction costs of carbon emissions decrease. When the penetration of PV reaches 40%, the total costs of the system are least. However, the penetration of PV has upper limit with the characteristic limits of thermal units and energy storage system.

6. Conclusion
In this paper, an optimal scheduling model of pumped storage in large-scale photovoltaic power system based on carbon trading is proposed, which achieves the purpose of improving the penetration and photovoltaic utilization of photovoltaics in power system. And it also improves the efficiency of low-carbon scheduling in the power system operation. The main conclusions are as follows,

1) The carbon emissions trading based on CDM is introduced into the economic dispatch of power system, which can realize the low-carbon economic operation of power system in this paper.
2) The pumped storage units are used for peak shaving in power system, which effectively improves the photovoltaic permeability and utilization efficiency of photovoltaic in power system, and greatly reduces the operating cost of the system.
3) The results of case study verify the validity and feasibility of the proposed optimal dispatching model for pumped storage in large-scale photovoltaic power system based on carbon trading. Between the comparison of the system with and without pumper storage, the optimization results show that with pumper storage can make the system operate more economically.

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