Coordinated operation strategy of hybrid storage system in wind power peak shaving scenarios

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Abstract: With more wind power being integrated into the power grid, its random and intermittent output has brought great impact on wind power utilisation. The new type of liquid compressed air energy storage has the advantages of high energy density, large capacity and free from geographical constraints. It can be used as a peak shaving device for wind farms to improve the accommodation of wind power, but its flexibility is relatively limited. Although electrochemical storage is flexible, large capacity requirements can lead to large costs when used for peak shaving. Considering the power and electricity capacity characteristics of different storage system as well as the output characteristics of wind farm, a hybrid storage system consisting of a new type of liquid compressed air energy storage and electrochemical storage is proposed for peak shaving of wind farm. Considering the power efficiency characteristics of storage system, a linear model for different storage is established. Then a mixed integer programming model is established to maximise the return of a wind farm under the cooperation mode of hybrid storage system in a wind farm. A case study shows that the proposed hybrid storage coordinated operation strategy can effectively improve the wind farm income and the accommodation of wind power.

1 Introduction

The randomness and volatility characteristics of wind power have brought some problems to its accommodation in the grid. Energy storage technology, with advantages of quick regulation speed and flexible configuration, has broad application in many fields, including being applied to help the consumption of new energy [1–3].

The energy type of storage represented by pumped storage and compressed air energy storage can effectively improve the wind power consumption level, while reducing the peak shaving pressure in a certain extent, by charging during the valley load period and discharging into the grid during the peak load period [4–6]. Pumped storage and conventional compressed air energy storage is often influenced by geographical constraint, but the new liquid compressed air energy storage (LCAES) is free from this constraint. At the same time, it has great advantages in storage density and removable storage, and many researches and experimental tests have been carried out both at home and abroad [7–10].

On the other hand, the above flexibility of the energy type storage is relatively limited, which causes difficulties in dealing with the fluctuation of wind power in short time scale. Although the regulation of the power type of storage like electrochemical storage is flexible, there is large capacity requirement for power and energy in wind power peak shaving scenarios, which means the cost cannot be underestimated.

Based on this, a hybrid storage system is a beneficial attempt by combining a new type of LCAES and electrochemical storage for peak shaving of wind farms. The advantages of different storage can be taken to get better peak shaving effect under certain cost.

Under the new energy peak shaving scenario, the combined operation model of wind farm and energy storage is described using the unit commitment model in the literature [4, 5, 11], however, some constraints remain non-linear, which reduces the reliability of the optimal solution and it is lack of consideration for the nature of storage power efficiency. An improved particle swarm optimisation algorithm is used to solve the unit commitment model, which still has the risk of convergence to the local optimum in [12].

In view of the insufficiency of models and algorithms in above literatures, a mixed linear integer programming model is proposed to ensure the effectiveness of the optimal solution by modelling and analysing the power efficiency characteristics of different storage system and linearising of different constraints. The case study shows the rationality of the new algorithm, and that coordinated operation strategy of hybrid storage can improve the performance of the wind farm significantly comparing the single storage model.

2 Efficiency characteristics of storage system

The charge and discharge efficiency characteristics of the storage system can be described by the power-efficiency curve. Different storage system has different efficiency characteristics, for example, when the power of liquid compressed air energy is close to the rated power, the efficiency is higher, and the efficiency decreases obviously when the power output gets far from the rated range, but the electrochemical storage is different, its efficiency is relatively stable, close to a constant.

However, the introduction of the power efficiency relationship usually adds non-linear constraints to the optimisation model, so linear processing is necessary to improve the validity of the solution. The method is shown in Fig. 1.

In Fig. 1, the original curve is a non-linear curve, representing the efficiency characteristics of storage system of the LCAES, a stepped curve is used to fit with in order to linearise energy constraint in the following. The charge and discharge operating intervals are divided into three segments to be fitted.
For electrochemical storage, there are the following characteristics:

\[
P_2 = 0 \\
\eta_2 \simeq \eta_1 \\
P_3 = 0 \\
\eta_1 \simeq \eta_4
\]

Thus, the more intuitive power efficiency curve is shown in Fig. 2. For the general pumped storage power, its charging power of single pumping pump is narrow, efficiency usually seen as a constant, but the discharge power can be adjusted in a certain range. The power efficiency curve is as follows, and non-linear part can be linearised in accordance with the method mentioned above (Fig. 3).

In this section, the power efficiency model of the storage system is established and linearised to ensure the validity and reliability of the algorithm under the optimal operation strategy.

### 3 Coordinated operation optimisation model of hybrid storage system for peak shaving

#### 3.1 Optimisation objective function

The objective is to optimise the sum of amount of electricity from wind farm into grid and net electricity increment of hybrid storage system minus the operation cost including start-up/shut-down and hot standby costs, considering power constraint, electricity capacity constraint, start-up and shut-down constraint in hybrid storage system and power constraint of wind farm.

The time of use (TOU) price is not considered here. If the TOU price is needed to consider, the income and cost in the objective function can be converted correspondingly

\[
F = \sum_{t=1}^{T} \left[ P_{g1}(t) + P_{g2}(t) + P_{g3}(t) + P_{g4}(t) + P_{o1}(t) + P_{o2}(t) \right] \\
+ \left[ P_{s1}(t) + P_{s2}(t) + P_{s3}(t) \right] \cdot \Delta T \\
+ \left[ Q_{s1}(T) - Q_{s2}(0) \right] \cdot \eta_{ci} + \left[ Q_{s2}(t) - Q_{s2}(0) \right] \cdot \eta_{bi} \\
- \sum_{t=1}^{T} \left[ y_{i1}(t) \cdot C_{s11} + y_{i2}(t) \cdot C_{s12} \right] \\
- \sum_{t=1}^{T} \left[ y_{i1}(t) \cdot C_{s21} + y_{i2}(t) \cdot C_{s22} \right]
\]

where \( P_{g1}(t), P_{g2}(t), P_{g3}(t), P_{g4}(t), P_{o1}(t), P_{o2}(t) \) represent the values of LCAES in six segments at time \( t \), as shown in Fig. 1, \( P_{s1}(t), P_{s2}(t), P_{s3}(t) \) represent the segmentation power of the charging system, and the sum represents the charging power, \( P_{s4}(t) \), \( P_{s5}(t), P_{s6}(t) \) represent the segmentation power of the discharging system, and the sum represents the discharging power, \( P_{s7}(t) \), \( P_{s8}(t) \), \( P_{s9}(t) \) represent the charging power and the discharge power of the electrochemical storage system at time \( t \), and the sum of \( P_{s10}(t) \) and \( P_{s11}(t) \) represents the power value of the electrochemical storage system, \( P_{s}(t) \) represents the value of wind power at time \( t \), \( \Delta T \) represents the time interval, 15 min here. \( T \) represents the length of the optimisation plan, 24 h here. \( Q_{s1}(T) \) represents the storage of LCAES at time \( T \), \( Q_{s2}(0) \) represents the initial power storage of LCAES. \( \eta_{ci} \) represents equivalent efficiency of LCAES power generation system. \( Q_{s2}(T) \) represents the storage of the electrochemical storage system at time \( T \), \( Q_{s2}(0) \) represents the initial power storage of the electrochemical storage system. \( \eta_{bi} \) represents equivalent efficiency of power generation system of the electrochemical storage system. \( y_{11}(t), y_{12}(t), y_{21}(t), y_{22}(t) \) represent the start-up operation index of the LCAES, the start-up operation index of the discharge system, the hot standby state of the charging system and the hot standby state of the discharge system. \( C_{s11}, C_{s12}, C_{s21}, C_{s22} \) represent the cold start-up cost of the charging system of LCAES, the cold start-up cost of the discharge, the hot standby cost of the charging system and the hot standby cost of the discharge system.

#### 3.2 Constraint conditions

(i) Wind power output constraint

\[
0 \leq P_{w}(t) \leq P_{r}(t)
\]

where \( P_{w}(t) \) represents the predicted value of wind power at time \( t \).
(ii) Power constraints of electrochemical storage

\[ P_{b1\text{max}} \cdot u_{b1}(t) \leq P_{b1}(t) \leq 0 \quad (4) \]
\[ 0 \leq P_{b2}(t) \leq P_{b2\text{max}} \cdot u_{b2}(t) \quad (5) \]
\[ u_{b1}(t) + u_{b2}(t) = 1 \quad (6) \]

where \( u_{b1}(t), u_{b2}(t) \) represent the charge and discharge state of electrochemical storage. \( P_{b1\text{max}} \) represents the maximum charge power of electrochemical storage, with negative values. \( P_{b2\text{max}} \) represents the maximum discharge power of electrochemical storage, with positive values.

(iii) Electrical constraints of electrochemical storage

\[ \Delta Q_b(t) = \frac{P_{g1}(t) \cdot \eta_{b1} + P_{g2}(t) \cdot \eta_{b2}}{\eta_{b3}} \cdot \Delta T \quad (7) \]
\[ Q_b(t) = Q_b(t-1) - \Delta Q_b(t) \quad (8) \]
\[ Q_{b\text{min}} \leq Q_b(t) \leq Q_{b\text{max}} \quad (9) \]

where \( \Delta Q_b(t) \) represents the energy increment of electrochemical storage at time \( t \). \( Q_b(t) \) represents the amount of electricity of electrochemical storage. \( Q_{b\text{min}}, Q_{b\text{max}} \) represent the minimum limit and maximum limit of electrochemical storage.

(iv) Power and state constraints of the charging system of LCAES

\[ P_{g1\text{min}} \cdot u_{g1}(t) \leq P_{g1}(t) \leq P_{g1\text{max}} \cdot u_{g1}(t) \quad (10) \]
\[ P_{g2\text{min}} \cdot u_{g2}(t) \leq P_{g2}(t) \leq P_{g2\text{max}} \cdot u_{g2}(t) \quad (11) \]
\[ P_{g3\text{min}} \cdot u_{g3}(t) \leq P_{g3}(t) \leq P_{g3\text{max}} \cdot u_{g3}(t) \quad (12) \]
\[ u_{g1}(t) + u_{g2}(t) + u_{g3}(t) + v_{1}(t) + w_{1}(t) = 1 \quad (13) \]
\[ y_{1}(t) + z_{1}(t) = 1 \quad (14) \]
\[ y_{1}(t) - z_{1}(t) = \lfloor 1 - w_{1}(t) \rfloor - \lfloor 1 - w_{1}(t-1) \rfloor \quad (15) \]

where \( u_{g1}(t), u_{g2}(t), u_{g3}(t) \) are 0–1 two valued variables, representing the state of the charging system in the three power segments at time \( t \). \( v_{1}(t), w_{1}(t) \) represent the hot standby state and shutdown state of the LCAES charging system. \( y_{1}(t), z_{1}(t) \) represent that the LCAES charging system changes from the shutdown to non-stop state, from non-stop state to stop. \( P_{g1\text{min}}, P_{g1\text{max}}, P_{g2\text{min}}, P_{g2\text{max}} \) represent the segment boundary value of the LCAES charging system.

(v) Power and state constraints of the discharging system of LCAES

\[ P_{g4\text{min}} \cdot u_{g4}(t) \leq P_{g4} \leq P_{g4\text{max}} \cdot u_{g4}(t) \quad (16) \]
\[ P_{g5\text{min}} \cdot u_{g5}(t) \leq P_{g5} \leq P_{g5\text{max}} \cdot u_{g5}(t) \quad (17) \]
\[ P_{g6\text{min}} \cdot u_{g6}(t) \leq P_{g6} \leq P_{g6\text{max}} \cdot u_{g6}(t) \quad (18) \]
\[ u_{g4}(t) + u_{g5}(t) + u_{g6}(t) + v_{2}(t) + w_{2}(t) = 1 \quad (19) \]
\[ y_{2}(t) + z_{2}(t) = 1 \quad (20) \]
\[ y_{2}(t) - z_{2}(t) = \lfloor 1 - w_{2}(t) \rfloor - \lfloor 1 - w_{2}(t-1) \rfloor \quad (21) \]

where \( u_{g4}(t), u_{g5}(t), u_{g6}(t) \) are 0–1 two valued variables, representing the state of the discharging system in the three power segments at time \( t \). \( v_{2}(t), w_{2}(t) \) represent the hot standby state and shutdown state of the LCAES discharging system. \( y_{2}(t), z_{2}(t) \) represent that the LCAES discharging system changes from the shutdown to non-stop state, from non-stop state to stop. \( P_{g4\text{min}}, P_{g4\text{max}}, P_{g5\text{min}}, P_{g6\text{min}} \) represent the segment boundary value of the LCAES discharging system.

(vi) Electrical constraints of the LCAES system

\[ \Delta Q_g(t) = \left[ P_{g1}(t) \cdot \eta_{g1} + P_{g2}(t) \cdot \eta_{g2} + P_{g3}(t) \cdot \eta_{g3} + P_{g4}(t) \cdot \eta_{g4} + P_{g5}(t) \cdot \eta_{g5} + P_{g6}(t) \cdot \eta_{g6} \right] \cdot \Delta T \quad (22) \]
\[ Q_{g\text{min}} \leq Q_g(t) \leq Q_{g\text{max}} \quad (23) \]
\[ T_{1\text{min}} + T_{2\text{min}} - T_m \cdot \sum_{k=1}^{n} w_k(k) \geq z_k(t) \cdot T_{1\text{min}} + T_{2\text{min}} \quad (24) \]

where \( \Delta Q_g(t) \) represents the energy increment of the LCAES at time \( t \). \( Q_g(t) \) represents the amount of electricity of LCAES. \( Q_{g\text{min}}, Q_{g\text{max}} \) represent the minimum limit and maximum limit of LCAES.

(vii) Minimum downtime constraint of the LCAES system

\[ \left[ P_{g1}(t) + P_{g2}(t) + P_{g3}(t) + P_{g4}(t) + P_{g5}(t) + P_{g6}(t) \right] \quad (25) \]
\[ \left[ P_{g1}(t) + P_{g2}(t) + P_{g6}(t) \right] + P_{g4}(t) \leq P_{g}(t) \quad (26) \]

where \( T_{1\text{min}}, T_{2\text{min}} \) represent the minimum allowable downtime for the charging system and discharge system. If there is a minimum run time, the same method can be used.

(viii) Wind farm total power constraints in grid

\[ \left[ P_{g1}(t) + P_{g2}(t) + P_{g3}(t) + P_{g4}(t) + P_{g5}(t) + P_{g6}(t) \right] \quad (27) \]

where \( P_{g}(t) \) represents the wind power limits allowed for in-grid access.

Several power sources including hybrid storage system in this paper can be adjusted at the time interval (15 min), therefore, climbing constraints are removed here.

4 Case study

Figs. 4–6 show the wind curtailment power of a wind farm in China under channel restriction in three consecutive days. In the local area as we can see, although the average value is near 50 MW in this study, it is not smooth and flat, and its fluctuation characteristics will bring about the cost and efficiency loss to the large capacity energy storage like single liquid compressed air storage and pump storage. On the other hand, the lasting time of the wind curtailment continues for about 8 h, which means that a sufficient capacity storage system is required, and that this capacity may be larger.
for wind farm clusters, so single electrochemical storage for peak shaving has a significant cost constraint.

The data of one day above is selected to verify the hybrid storage system–wind farm coordinated operation optimisation model. The parameters used are as follows:

\[ Q_{\text{min}} = 30 \text{ MWh}, \quad Q_{\text{max}} = 400 \text{ MWh}, \quad P_{g1\text{min}} = -50 \text{ MW}, \quad P_{g1\text{max}} = -45 \text{ MW}, \quad P_{g2\text{min}} = -40 \text{ MW}, \quad P_{g2\text{max}} = -35 \text{ MW}, \quad \eta_2 = 0.75, \quad \eta_3 = 0.65, \quad P_{g3\text{min}} = 35 \text{ MW}, \quad P_{g3\text{max}} = 40 \text{ MW}, \quad P_{g4\text{min}} = 45 \text{ MW}, \quad P_{g4\text{max}} = 50 \text{ MW}, \quad \eta_4 = 0.65, \quad \eta_5 = 0.75, \quad \eta_{g5} = 0.85, \quad Q_{\text{f1}}(0) = 100 \text{ MWh}, \quad T_{\text{min}} = T_{\text{2min}} = 3 \text{ h}, \quad P_{\text{b1min}} = -5 \text{ MW}, \quad P_{\text{b2max}} = 5 \text{ MW}, \quad \eta_{\text{f1}} = 0.75, \quad \eta_{\text{f2}} = 0.95, \quad C_{\text{start1}} = C_{\text{start2}} = 40 \text{ MWh}, \quad \eta_{\text{f1}} = 0.7, \quad C_{\text{i1}} = C_{\text{i2}} = 5 \text{ MWh}.

In the above model, the constraints and objective functions have all been linearised, and MATLAB is used to solve with CPLEX.

Figs. 7, 8 and 9 show the output of a wind farm without storage system. Observing the output curve, the liquid compressed air energy can absorb the wind power near the rated power in the period of the abandoned air, and discharge as close as possible to the rated power when the channel is enough, which corresponds to the power efficiency characteristics of the storage. During the operation period of LCAES, the electrochemical storage can increase the charging power of LCAES by discharging, such as near the 5–8 time point, which corresponds to the coordinated operation strategy. The reasonable actions of two kinds of storage system verify the validity of the above calculation model.

Under the condition of no storage system, the equivalent total power gain of wind farm is 3258.7 MWh. Under the coordinated operation mode of hybrid storage, the equivalent total power gain of wind farm is 3463.4 MWh, increasing by 204.7 MWh. Under the independent operation mode of storages, the equivalent total power gain of wind farm is 3442.2 MWh, an increase of 183.5 MWh. This means an additional 11.6% improvement in the hybrid storage system.

A pumped storage hybrid storage with the same capacity is compared with the hybrid storage system above. The pumping unit uses two units, the efficiency is 0.9, the power range for each is 20–25 MW, the discharge system efficiency is 0.7, 0.8 and 0.9, and the cost of single pumping unit start-up costs 20 MWh, using the same model, the results are as follows.

Under the condition of no storage system, the equivalent total power gain of wind farm is 3258.7 MWh. Under the coordinated operation mode of hybrid storage, the equivalent total power gain of wind farm is 3558.3 MWh, increasing by 299.3 MWh. Under the independent operation mode of storage, the equivalent total power gain of wind farm is 3530.8 MWh, an increase of 272.1 MWh. This means an additional 10.0% improvement in the hybrid storage system. The whole situation is shown in Table 1.

It can be inferred that the coordination of mixed storage can produce additional benefits, because the electrochemical storage

\[ \text{Table 1 Comparison of coordinated mode with independent mode} \]

|                     | LCAES hybrid storage | Pumped storage hybrid storage |
|---------------------|----------------------|-------------------------------|
| coordinated mode    | 204.7 MWh            | 299.3 MWh                     |
| independent mode    | 183.5 MWh            | 272.1 MWh                     |
| mode increment      | 11.6%                | 10.0%                         |

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has a small time range of peaking and filling on the basis of whole day peaking shaving.

Therefore, it is further speculated that while the large capacity energy storage peak shaving operation, the greater the fluctuation of wind power on short time scales, the greater the revenue gain of hybrid storage coordination mode. In addition, hybrid storage in coordinated mode for peak shaving has additional added benefits, for example, large capacity energy storage has less regulation operation due to electrochemical storage.

For differences in efficiency, we can see that the pumped storage revenue is higher than the new LCAES. However, the construction of pumped storage has significant geographical factors, and when the efficiency of LCAES increases with the technology, it can be used as an alternative to the construction of pumped storage.

5 Conclusions

Due to the power output characteristics of wind farm, the wind curtailment phenomenon in large-scale wind farms occurs frequently. Using a certain energy storage system for peak shaving and valley filling can effectively reduce abandoned air and improve the income of wind farms. In this paper, based on a new LCAES, considering the different storage power efficiency characteristic, a hybrid storage coordinated operation mode in wind farm peaking shaving is proposed and transformed into a mixed integer programming model to get optimum solution.

The case result verifies the correctness of the model and the effectiveness of the coordinated strategy:

(i) Hybrid storage coordinated operation mode will make additional revenue, one is the income of electrochemical storage in small scale ‘peak shaving’, the other is the efficiency improvement of large-scale energy storage due to regulation of electrochemical storage.

(ii) Due to the difference in efficiency, the new LCAES has a certain gap in the comprehensive income compared with the pumped storage. However, it has no geographical restrictions, and can be used as complementary scenarios for pumped storage in the future when the efficiency is gradually improved.

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