Joint Planning Of Energy Storage and Transmission Considering Wind-Storage Combined System and Demand Side Response

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Abstract. In response to the new requirements of the operation mode of wind-storage combined system and demand side response for transmission network planning, this paper presents a joint planning of energy storage and transmission considering wind-storage combined system and demand side response. Firstly, the charge-discharge strategy of energy storage system equipped at the outlet of wind farm and demand side response strategy are analysed to achieve the best comprehensive benefits through the coordination of the two. Secondly, in the general transmission network planning model with wind power, both energy storage cost and demand side response cost are added to the objective function. Not only energy storage operation constraints but also demand side response constraints are introduced into the constraint condition. Based on the classical formulation of TEP, a new formulation is developed considering the simultaneous addition of the charge-discharge strategy of energy storage system equipped at the outlet of the wind farm and demand side response strategy, which belongs to a typical mixed integer linear programming model that can be solved by mature optimization software. The case study based on the Garver-6 bus system shows that the validity of the proposed model is verified by comparison with general transmission network planning model. Furthermore, the results demonstrate that the joint planning model can gain more economic benefits through setting up different cases.

1. Introduction

In recent years, structure and operation mode of modern power system have changed greatly with the development of renewable energy, energy storage technology and load side management [1-4]. The source side or the load side change will have a substantial impact on the transmission network planning. That’s because it is based on power and load forecasting data. Therefore, it is necessary to take full account of the impacts of wind farms and energy storage systems as well as load side management on planning.

Now, there is the discussion on the combination of energy storage planning and transmission network planning [5-6] and the combination of demand side response and transmission network planning [7-10]. However, there is not much research on the transmission network planning considering the two simultaneously. For example, literature [5] establishes a two layers planning model of a transmission system considering only the operation of a wind-storage combined system. A
transmission planning model only based on demand side response mechanism is established in the literature [7].

Therefore, this paper proposes a joint planning of energy storage and transmission considering wind-storage combined system and demand side response. Energy storage operation constraints and demand side response constraints are introduced. On this basis comprehensive resources planning is realized. The example system shows that the model is comparable, and the joint planning model can achieve more significant economic benefits.

2. Operation strategy analysis

2.1. Operation strategy of wind-storage combined system
To alleviate the pressure on the system regulating capacity and effectively reduce wind power curtailment, energy storage system equipped at the outlet of wind farm can be used to smooth stochastic fluctuation of wind farm output power. Combined with energy storage characteristics that frequent charge-discharge can shorten the cycle life, the operating strategies are proposed: in the planning model, the constraints of energy storage operation and daily charge-discharge are introduced. In this way energy storage configuration capacity is optimized to meet the requirement of wind wave rate and to maximize utilization ratio of wind resources.

2.2. Demand side response strategy
Demand side response is that electric power department encourages users to change power consumption mode through administrative and economic means, which can achieve peak shaving, valley filling, load transfer and relieve system regulating pressure. The numbers of new power plants and new transmission lines can be reduced on the planning layer [4]. Therefore, this paper proposes the following demand side response strategy only considering interruptible load and incentive load response: the demand side response strategy is introduced in the planning transmission system with wind power. Under the system security constraints, when the load is high, the wind power supply is less or the system regulation capacity is insufficient, the users who sign interruptible load protocols are guided to reduce power consumption. When the load is low, the wind power supply is adequate and the system regulation capacity is insufficient, the users who sign incentive load protocols are guided to increase power consumption. Otherwise, there will be wind power curtailment. In this way, the costs of transmission line and wind power curtailment are reduced simultaneously.

3. Mathematical model

3.1. Objective function
The objective function of the model consists of four parts: investment cost of transmission line $f_{\text{line}}$, investment cost of energy storage system $f_{\text{ess}}$, cost of wind power curtailment $f_{\text{wind}}$ and compensation cost of demand side response $f_{\text{dsr}}$. Since the model of this paper takes the time dimension into account, all the cost functions in the objective function are translated into annual investments.

$$
\min f = f_{\text{line}} + f_{\text{ess}} + f_{\text{wind}} + f_{\text{dsr}}
$$

$$
f_{\text{line}} = \frac{i(1+i)^n}{(1+i)^n-1} \sum_{i=1}^{N} c_i n_i^p
$$

$$
f_{\text{ess}} = (1+r_{op} + r_{ma} + r_{v})N_{de} \sum_{k=1}^{K} \left( c_p P_{ert,k} + c_{\text{es}} e_{ert,k} \right)
$$

$$
f_{\text{wind}} = \sum_{j=1}^{J} \sum_{s=1}^{S} d_s \sum_{t=1}^{T} c_{\text{w}} \left( p_{w,t,s,j}^{\text{max}} - p_{w,t,s,j} \right)
$$
\[ f_{dis} = \sum_{s=1}^{T} \sum_{i=1}^{d_s} \left( c_i^+ \sum_{m \in \Omega^c} \Delta P_{L,i,s,m}^+ + c_i^c \sum_{m \in \Omega^c} \Delta P_{L,i,s,m}^c \right) \] (5)

In equation (2), \( i \) is the discount rate and \( n \) is service life cycle. \( ij \) represents the branch of the head and the tail nodes numbered \( i \) and \( j \), \( c_{ij} \) is the cost of single branch \( ij \), and \( n_{ij}^\text{max} \) is the extension number of the \( p \)-th candidate branch \( ij \). \( \Omega^c \) is the set of candidate branches. In equation (3), \( r_{op} \), \( r_{ma} \), and \( r_{w} \) are cost conversion coefficients of the operation, maintenance and disposal of the energy storage system. \( c_p \) and \( c_c \) are the unit power and unit capacity costs of energy storage system. \( P_{i,t,s}^\text{max} \) and \( c_{i,t,s}^\text{max} \) are the rated power and rated capacity of the energy storage system allocated at the node \( k \). \( \Omega_{ij} \) is the set of energy storage nodes to be configured. In equation (4), \( \Omega_7 \) is the set of wind farms. The letter 's' stands for a typical day, the number of days of which is \( d_s \), \( T \) is the number of periods per typical day, \( \Gamma^c \) is the set of typical days, and \( c_w \) is cost of unit wind power curtailment. \( P_{w,s,t,j}^\text{max} \) and \( P_{w,s,t,j}^\text{max} \) are the maximum output and actual output of wind farm \( j \) on typical day \( s \) within hour \( t \). In equation (5), \( c_i^+ \) and \( c_i^c \) are unit compensation costs of interruptible load and incentive load within hour \( t \). \( \Omega^c_7 \) and \( \Omega_7 \) are the sets of interruptible load and incentive load. \( \Delta P_{L,i,s}^+ \) is the increase of incentive load on typical day \( s \) within hours \( t \) for node \( m \) and \( \Delta P_{L,i,s}^\text{dec} \) is the decrement of interruptible load on typical day \( s \) within hour \( t \) for node \( m \).

3.2. Constraints
The primary constraints of the model include the system DC power flow constraints, conventional power plant operation constraints, wind farm operation constraints, energy storage system operation constraints, demand side response constraints and system standby constraints.

3.2.1. System DC power flow constraints

\[
P_{g,s,t} + P_{w,s,t,j} - A^e P_{g,s,t} - A^p P_{g,s,t} = P_{l,s,t} - \Delta P_{L,s,t}^+ - \Delta P_{L,s,t}^c
\] (6)

\[
\begin{align*}
p_{g,s,t} - b_{ij} n_{ij}^p (\theta_{i,t,s} - \theta_{j,t,s}) & = 0, & \left( p_{g,s,t} \right)^p & \leq n_{ij}^p p_{ij}^\text{max}, & \forall (i, j) \in \Omega^c_7; \\
\left| p_{g,s,t} - b_{ij} (\theta_{i,t,s} - \theta_{j,t,s}) \right| & \leq \Delta \left( 1 - n_{ij}^p \right), & \left( p_{g,s,t} \right)^p & \leq n_{ij}^p p_{ij}^\text{max}, & \forall (i, j) \in \Omega^c_7; \\
p \in (1, 2, \ldots, n_{ij}^\text{max}), \theta_{ref,t,s} & = 0.
\end{align*}
\] (7)

In equation (6), \( P_{g,s,t} \), \( P_{w,s,t,j} \) and \( P_{l,s,t} \) stand for output vectors of conventional power plant, output vector of wind-storage combined system and load active demand vector at each node on typical day \( s \) within hour \( t \), respectively. \( A^e \) and \( A^p \) stand for node-branch incidence matrices of existing and candidate lines. \( P_{g,s,t}^\text{max} \) and \( P_{w,s,t,j}^\text{max} \) are branch active power vectors of existing and candidate lines on typical day \( s \) within hour \( t \), respectively. In equation (7), \( p_{g,s,t}^\text{max} \) and \( p_{w,s,t,j}^\text{max} \) are active power of existing and candidate branch \( ij \) on typical day \( s \) within hour \( t \), respectively. \( b_{ij} \) is admittance of branch \( ij \). \( n_{ij}^\text{max} \) is the number of existing line \( ij \) and \( n_{ij}^\text{max} \) is the maximum optional number of candidate line \( ij \). \( \theta_{i,t,s} \), \( \theta_{j,t,s} \) and \( \theta_{ref,t,s} \) are voltage phase angles of bus \( i \), bus \( j \) and slack bus on typical day \( s \) within hour \( t \), respectively. \( p_{ij}^\text{max} \) is the maximum active power limit of branch \( ij \).

3.2.2. Conventional power plant operation constraints

\[
p_{g,s,t}^\text{min} \leq P_{g,s,t} \leq P_{g,s,t}^\text{max}, \quad \Delta P_{g,s,t}^\text{min} \leq P_{g,s,t-1,s} - P_{g,s,t-1,s} \leq \Delta P_{g,s,t}^\text{max}
\] (8)

Where max and min stand for high/low limit of corresponding variables. \( P_{g,s,t}^\text{max} \) and \( P_{g,s,t-1,s}^\text{max} \) are active power of conventional power plant at typical day \( s \) within hour \( t \) and hour \( t-1 \), respectively. \( \Delta P_{g,s,t}^\text{min} \) and \( \Delta P_{g,s,t}^\text{max} \) stand for equivalent landslide and climbing rate of conventional power plant at typical day \( s \) within hour \( t \), respectively.

3.2.3. Wind farm operation constraints

\[
0 \leq P_{w,s,t,j} \leq P_{w,s,t,j}^\text{max}, \quad P_{w,s,t,j} = P_{w,s,t,j} - P_{w,s,t,j} \leq \gamma_{ws}
\] (9)
Where $p_{w,t,i,j}$ and $p_{es,t,i,j}$ are actual output of wind farm $j$ and charge-discharge power of energy storage system $j$ on typical day $s$ within hour $t$, respectively. $p_{es,t,i,j}$ and $p_{w,t,i,j}$ are output of wind-storage combined system $j$ on typical day $s$ within hour $t$ and hour $t-1$, respectively. $\gamma_{ws}$ is the fluctuation limit of output of wind-storage combined system.

### 3.2.4. Energy system operation constraints

\[
0 \leq e_{es,t,i,j} \leq e_{es,t,i,j}^* - p_{es,t,i,j} \leq p_{es,t,i,j} - e_{es,t,i,j}^* + e_{es,t,i,j}^{min} \leq p_{es,t,i,j}^* \leq p_{es,t,i,j}^{max} \quad (10)
\]

\[
e_{es,t+1,i,j} = e_{es,T,s,k} \cdot \Delta t \cdot e_{es,t,i,j} + p_{es,T,s,k} \cdot \Delta t, e_{es,T,s,k} = e_{es,t-1,i,j} + p_{es,t-1,i,j} \cdot \Delta t \quad (11)
\]

In equation (11), $e_{es,t,i,j}$ is capacity of energy storage system $j$ on typical day $s$ within hour $t$. In equation (12), $e_{es,t,i,j}$ and $e_{es,t,i,j}^*$ are storage energy of energy storage system $k$ on typical day $s$ within hour 1, $T$ and $t$, respectively. $p_{es,T,s,k}$ and $p_{es,t-1,i,j}$ are charge-discharge power of energy storage system $k$ on typical day $s$ within hour $T$ and $t-1$, respectively. $At$ is time interval, 1h.

\[
\text{flag}_{t,s,k} = \text{sign}(p_{es,t,i,j}) = \begin{cases} 1, & p_{es,t,i,j} > 0 \\ 0, & p_{es,t,i,j} = 0 \\ -1, & p_{es,t,i,j} < 0 \end{cases} \quad (12)
\]

\[
\text{flag}_{t,s,k}^* \leq \frac{1}{2} u_{t,s,k}^d + (1 - u_{t,s,k}^d)M, \text{ flag}_{t,s,k} \geq -\frac{1}{2} u_{t,s,k}^c + (1 - u_{t,s,k}^c)M,
\]

\[
\begin{align*}
&u_{t,s,k}^c + u_{t,s,k}^d = 1, u_{t,s,k} = u_{t,s,k}^c - u_{t,s,k}^d, \\
&\left| \frac{1}{2} \sum_{t=2}^{T} |u_{t,s,k} - u_{t-1,s,k}| \right| \leq N_{max}
\end{align*}
\]

In equation (12), $\text{flag}_{t,s,k}$ is variables representing charging and discharging state of energy storage, and possible values are -1, 0 and 1. In equation (13), $u_{t,s,k}^c$ and $u_{t,s,k}^d$ are 0-1 variables representing charging and discharging state of energy storage. $u_{t,s,k}$ is the variables representing charging and discharging state of energy storage, and possible values are -1 and 1. $M$ is a big number. $N_{max}$ is the maximum charge-discharge times of an energy storage system on each typical day.

### 3.2.5. Demand side response constraints

\[
u_{t,s,k}^+ + u_{t,s,k}^- \leq 1, 0 \leq \Delta p_{L,s,k}^+ \leq \Delta p_{L,s,k}^{max}, 0 \leq \Delta p_{L,s,k}^- \leq \Delta p_{L,s,k}^{max} \\
\sum_{t=1}^{T} u_{t,s,k}^+ \leq T_{max}, t = 1, 2, \ldots, T - T_{max}; \sum_{t=1}^{T} u_{t,s,k}^- \leq T_{max}, t = 1, 2, \ldots, T - T_{max} \quad (14)
\]

In equation (14), $u_{t,s,k}^+$ and $u_{t,s,k}^-$ are 0-1 variables representing the operation state of incentive load and interruptible load. In equation (15), $T_{max}$ and $T_{max}$ are the maximum continuous time of operation of incentive load and interruptible load.

### 3.2.6. System standby constraints

\[
\begin{align*}
&\sum_{t=1}^{T} p_{t,s,k}^{max} + \sum_{j} p_{w,t,s,j} \geq \sum_{k} p_{L,s,k} + \sum_{m} \Delta p_{L,s,k}^m + R_{u,s}, \\
&\sum_{t=1}^{T} p_{t,s,k}^{max} + \sum_{j} p_{w,t,s,j} \geq \sum_{k} p_{L,s,k} + \sum_{m} \Delta p_{L,s,k}^m - R_{d,s}
\end{align*}
\]

Where $R_{u,s}$ and $R_{d,s}$ are the positive and negative rotating reserve capacity limit within hours $t$.

### 3.3. Model solving

The model established in this paper belongs to a typical mixed integer linear programming model. The objective function consists of equations (1)-(5), the constraints consist of equations (6)-(16) and decision variables consist of integer and continuous types. Integer variables are $w_t$, $u_{t,s,k}$, $w_{t,s,k}$, $u_{t,s,m}$ and so on, which determine transmission line planning scheme, charging and discharging state of energy storage system and participation status of demand side response load, respectively. Continuous
variables are $p_{ij,t,s}$, $p_{p,ij,t,s}$, $p_{g,t,s}$, $p_{w,t,s}$, $Δp_{L,t,s}$, $Δp_{-L,t,s}$, $p_{es,t,s}$, $e_{es,t,s}$, $p_{re,k}$ and $θ_{i,t,s}$. The case has been implemented on a personal computer, using GUROBI 7.0.2 under MATLAB.

4. Case study

4.1. Example system settings

This paper takes the Garver-6 bus system widely used by transmission network planning researchers as an example system [4]. System parameters are available in the literature [4] and original topology is shown in figure 1. Suppose a new power plant bus is added and total maximum load forecast is increased to 760MW. There are 15 possible expansion corridors, and the maximum number of lines allowed for each corridor is set to 3. A wind farm with a capacity of 240MW is added at bus 3. It is assumed that all load nodes in the system can participate in incentive response, and nodes 2, 4 and 5 participate in interruptible response. Line cost is 100 million RMB/km. Cost of unit wind power curtailment is 0.61RMB/kWh [5]. The compressed-air system is selected as the energy storage system, and cost parameters [11-12] of which are shown in Table 1. The time-sharing compensation price of demand side response is shown in Table 2.

| Table 1. The cost parameters of energy storage system. |
|____________________________________________________________|
| $r_{op}$ | $r_{de}$ | $c_p$(RMB/kW) | $c_e$(RMB/kWh) |
| 0.01 | 0.05 | 200 | 4000 |

| Table 2. Compensation price. |
|-----------------------------|
| Compensation price (RMB/kWh) | Rush hours 9:00-14:00 18:00-22:00 | Slack hours 0:00-7:00 | Other hours 7:00-9:00 14:00-18:00 22:00-24:00 |
| $c'_i$ | 0.1 | 0.5 | 0.3 |
| $c'_e$ | 0.5 | 0.1 | 0.3 |

4.2. Planning result analysis

4.2.1. Validity comparison In order to make the result of this model comparable, this section does not consider the wind power integration, energy storage integration, and demand side response strategy without considering the fluctuations of original power and load. The planning result is obtained by solving model, which is shown in figure 2. The result is in good agreement with the results of literature [4] by means of stepwise inverse method and literature [13] using Benders decomposition method, which validates the validity of the model of this paper.

![Figure 1. Initial network topology.](image1)

![Figure 2. Optimal expansion plan result.](image2)
4.2.2. Comparison of results of different planning cases. To reflect advantages of synthetically considering the combination of energy storage system and demand side response as well as transmission network planning with wind power, four different cases are set up. Case 1: neither the energy storage system integration nor the demand side response strategy is considered. Case 2: only demand side response strategy is considered. Case 3: only energy storage system is considered. Case 4: both energy storage system integration and demand side response strategies are considered. The planning results are obtained by solving models: planning schemes under different cases are shown in table 3, and planning costs under different cases are shown in table 4.

Analyses are conducted on the planning results in tables 3 and 4:

Compared with case 1, it can be seen that line cost is reduced by 3.41 million RMB and cost of wind power curtailment is reduced by 6.05 million RMB in case 2, meanwhile cost of wind power curtailment is reduced by 48.55 million RMB in case 3. By comparing cases 2 and 3, it can be seen that cost of wind power curtailment drops to 0, and the annual total investment cost reaches the minimum. Results demonstrate that demand side response strategy can reduce peak load for load curve, thereby reducing the investment costs of transmission lines. An energy storage system is added to the side of the wind farm can not only stabilize wind generation fluctuation but also improve system regulation capability. In addition, considering the influence of energy storage system and demand side response on planning, wind power capacity is improved with economic benefits.

Table 3. Planning schemes under different cases.

| Case | Route planning scheme | Stored energy planning power |
|------|-----------------------|-----------------------------|
| case1 | 2-6(3) 2-5(1) 3-5(1) 4-6(2) | 0 |
| case2 | 2-6(3) 3-5(1) 4-6(2) | 0 |
| case3 | 2-6(3) 2-5(1) 3-5(1) 4-6(2) | 44.04MW |
| case4 | 2-6(3) 3-5(1) 4-6(2) | 41.66MW |

Table 4. Planning costs under different cases. unit: Million RMB

| Case | $f_{\text{line}}$ | $f_{\text{EES}}$ | $f_{\text{wind}}$ | $f_{\text{stor}}$ | $f$ |
|------|-----------------|-----------------|-----------------|-----------------|-----|
| case1 | 22.36 | 0 | 51.96 | 0 | 74.32 |
| case2 | 18.95 | 0 | 45.91 | 4.60 | 69.46 |
| case3 | 22.36 | 10.67 | 3.41 | 0 | 36.44 |
| case4 | 18.95 | 10.10 | 0 | 2.59 | 31.64 |

Figure 3 shows energy storage charge-discharge power curve and SOC curve under case 4. Figure 4 presents fluctuation rate of output of integrated system under case 4.

5. Conclusion

The combined operation mode of wind farm and energy storage changes the output of the source, and demand side response patterns change the load side demand characteristics. Under the new situation, the transmission network planning faces the double challenges due to changes at source side and load.
side. Therefore, in the transmission network planning, it is necessary to comprehensively consider wind-storage combined system and demand side response.

The case study based on the Garver 6-bus system shows: compared with the model that takes only one factor (energy storage system equipped at the outlet of wind farm or demand side response strategy) into account, the proposed model that considers the mutual response of energy storage and demand side response can enhance the capacity of wind power utilization, optimize the energy storage configuration capacity and line planning scheme as well as bring the greatest economic benefits on the basis of ensuring the safe and reliable operation of the system.

Acknowledgments
This work is supported by the National Key R&D Program of China (2016YFB0900500). We would like to express our most sincere appreciation.

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