Research on operation strategy optimization method of multi-energy complementary new energy generation system

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Abstract. Qinghai province has a rich variety of energy, how to make the multi-energy complementary new energy generation system better participate in the multi-type market trading has become an important issue. Can complement each other in this article, through analysis of new energy power generation system in power generation, FM, load, and the structure of the secondary market, as well as benefits, build scenery storage and participate in ancillary service market strategy optimization model, and through the empirical analysis to study the electricity trading and energy storage and heat in peaking and frequency modulation strategy and returns, help to Qinghai province carry out the pluripotent complementary new energy power generation system involved in kinds of market transactions, as the nationwide can complementary and new energy power generation system in many model driven market transactions.

1. Introduction

1.1. Operation mode of power generation market.

(1) Participation way

The market participants of the multi-energy complementary new energy generation system in the peak regulation market mainly include the units, power trading centers and dispatching institutions. The units involved in peak regulation mainly include photovoltaic and energy storage, whose core function is to regulate the peak of electricity consumption to ensure the stability of the system. The core function of the power trading center is to provide a platform for peak regulating market trading. The core function of the dispatching mechanism is to conduct the transaction of peak load adjustment on behalf of the user according to the price level of each peak load adjustment unit, the possible peak load adjustment shortage of the system and other factors.

The trading mode of multi-energy complementary new energy generation system participating in peak regulation market mainly includes free bidding and medium and long-term contract. However, in order to ensure an adequate and reliable supply of peak load capacity, peak load capacity is usually planned to some extent. Therefore, it is more feasible to participate in free bidding for part of peak load capacity and obtain the rest of peak load capacity in the form of medium and long-term contracts. Medium and long-term trading including ordinary medium and long-term contracts and options trading, options trading can not only ensure reliable supply of goods, trading and maintain market price stability,
namely the buyer to pay the cost of the option price in advance, in order to obtain in the specified period of time with the option to perform a fixed price to buy a commodity right, so this kind of way to trade with risk aversion a common options contracts are the main advantages.

(2) Revenue method
There are two main ways for the multi-energy complementary new energy generation system to participate in the peak regulation market. The second is to determine returns in medium- and long-term contracts. In the medium and long-term contract market, the contracted units immediately get the deposit in the form of option price. During each real-time trading period, the dispatching agency conducts real-time dispatching on the units by executing the peak load adjustment option to obtain the peak load adjustment power, and the units accordingly obtain the strike price cost of the option. If the unit fails to provide the service on time during the real-time dispatching of the peak-regulating service by the dispatching organization, the unit shall pay a certain compensation fee to the dispatching center, which is larger than the above payment fee, so as to regulate and constrain the behavior of the peak-regulating unit.

2. Operation strategy optimization method of Sunscape heat storage participating in auxiliary service market

2.1. Operational objective function.
In order to meet different operating constraints and obtain different operating benefits, this paper chooses the operating benefits of the multi-energy complementary new energy generation system as the objective function. At the same time, the operation constraints of different power sources, system load supply and demand and system rotation reserve are considered.

\[
\max I = \sum_{t=1}^{T} (R_{\text{wind}} + R_{\text{solar}} + R_{\text{ESS}} + R_{\text{sp}})
\]  

(1)

Electricity revenue from wind power and photovoltaic power generation
Electricity revenue per unit time of wind power

\[
R_{\text{wind}} = (C_{\text{TL}} + C_{\text{subsidy}} - C_{\text{cost}}) P_{\text{wind}}
\]  

(2)

Where, \(C_{\text{TL}}\) is the unit price of desulfurization, \(C_{\text{subsidy}}\) is the government subsidized electricity price, \(C_{\text{cost}}\) is the power generation cost of wind power, and \(P_{\text{wind}}\) is the grid-connected power.

Photovoltaic electricity yield per unit time

\[
R_{\text{solar}} = (C_{\text{TL}} + C_{\text{subsidy}} - C_{2}) P_{\text{solar}}
\]  

(3)

Where, \(C_{\text{subsidy}}\) is the government subsidized price of photovoltaic, \(C_{2}\) is the price of photovoltaic power generation cost, and \(P_{\text{solar}}\) is the grid-connected power of photovoltaic.

Energy storage, frequency regulation, and peaking return (FM power station net return model)
1) Energy storage and frequency modulation benefits
The net income from the battery energy storage system participating in frequency modulation consists of three parts, namely, the compensation obtained by the energy storage system participating in frequency modulation, the penalty for failing to meet the response index, and the cost caused by the life loss of the energy storage system, which can be expressed as follows:

\[
R_{\text{ESS}} = R_{\text{gross}} - P_{\text{penalty}} - C_{\text{loss}}
\]  

(4)

\[
R_{\text{gross}} = R_{\text{gross}}(\Delta t, P_E)
\]  

(5)

\[
P_{\text{penalty}} = P_{\text{penalty}}(\Delta t, P_E)
\]  

(6)
\[ C_{loss} = C_{loss} (\Delta t, P_E) \]  

(7)

In conclusion, the net income model of energy storage system participating in frequency modulation is:

\[ R_{ESS} (\Delta t, P_E) = R_{gross} (\Delta t, P_E) - P_{penalty} (\Delta t, P_E) - C_{loss} (\Delta t, P_E) \]  

(8)

Where, \( R_{ESS} \) represents the frequency modulation income of energy storage, \( R_{gross} \) represents the compensation obtained by the energy storage system participating in frequency modulation, \( P_{penalty} \) represents the penalty for failing to meet the response index, \( C_{loss} \) represents the cost caused by the life loss of the energy storage system, \( \Delta t \) represents the response time and output adjustment speed of the energy storage system, and \( P_E \) represents the adjustment accuracy of the energy storage system.

Energy storage peak regulation benefit

\[ R_{ESS2} = \sum_{i=1}^{\mathcal{I}} Q_{ESS}^i \cdot P_{Pl}^i \]  

(9)

Where, \( Q_{ESS}^i \) is the compensated power amount in the 1st gear (kWh in unit) contributed by energy storage battery, and \( P_{Pl}^i \) is the peak adjustment and clearing price in the 1st gear (yuan/kWh in unit).

\[ Q_{ESS} = \sum_{i=1}^{\mathcal{I}} Q_{ESS}^i \]  

(10)

Photothermal reserve and peak regulation income

\[ R_{csp} = \sum_{i=1}^{T} k_r (P_L + P_F + P_G + P_R) \]  

(11)

Where, \( R_{csp} \) represents the reserve income of solar thermal units, \( L, F, G, R \) is the error rate of forecasting load, wind power, photovoltaic and solar thermal power generation, \( k_r \) is the system reserve cost coefficient, and \( P_L \) is the load value at time \( t \).

\[ R_{csp2} = \sum_{i=1}^{\mathcal{T}} k_p |P_{st}| \]  

(12)

Where, \( R_{csp2} \) is the peak-regulating income of photothermal units, \( k_p \) is the peak-regulating capacity cost coefficient, and is the peak-regulating capacity at time \( t \). Among them:

\[ P_{st} = P_L - (P_F + P_G + P_R) \]  

(13)

2.2. Operating const\( P_{st} \)rains.

Real-time supply and demand balance constraint of load

\[ g_{wind,t} (1 - \varphi_{wind,t}) + g_{solar,t} (1 - \varphi_{solar,t}) + g_{ESS,t} (1 - \varphi_{ESS,t}) + g_{CSP,t} (1 - \varphi_{CSP,t}) + g_{GC,t} = L_t \]  

(14)

Where, \( \varphi_{wind,t}, \varphi_{solar,t}, \varphi_{ESS,t} \) and \( \varphi_{CSP,t} \) respectively represent the power utilization rate of wind power, photovoltaic power, energy storage and photothermal power generation; \( g_{wind,t}, g_{solar,t}, g_{ESS,t} \) and \( g_{CSP,t} \) respectively represent the wind power, photovoltaic power, energy storage and photothermal power generation output at time \( t \); \( g_{GC,t} \) represents the call rate of GC at time \( t \); \( L_t \) represents the
system load at time $t$. When GC is greater than 0, it indicates that the multi-energy complementary new energy generation system purchases electricity from GC to meet the insufficient power. When GC is less than 0, it indicates that the multi-energy complementary new energy generation system will output power to the public grid and obtain economic benefits.

Voltage current constraint

$$U_{i}^{\text{min}} \leq U_{i} \leq U_{i}^{\text{max}}$$

(15)

Where, $U_{i}^{\text{max}}$, $U_{i}^{\text{min}}$ are the minimum voltage of node $I$ (kv), the maximum voltage of node $I$ (kv), $I_{i}^{\text{min}}$ is the minimum current of line $i$-$j$ (a), $I_{i}^{\text{max}}$ is the maximum current of line $i$-$j$ (a).

Operating constraints of wind power

$$g_{w,t}^{\text{min}} \leq g_{w,t} \leq g_{w,t}^{\text{max}}$$

(16)

Where: $g_{w,t}$ is the output of wind turbine at time $t$; And $g_{w,t}^{\text{min}}$, $g_{w,t}^{\text{max}}$ are respectively the lower limit and upper limit of wind turbine output at time $t$.

Operating constraints of photovoltaic power generation

$$g_{pv,t}^{\text{min}} \leq g_{pv,t} \leq g_{pv,t}^{\text{max}}$$

(17)

$$g_{pv,t}^{\text{min}} = g_{pv,t}^{\text{pre}} - p_{\text{lim}}$$

(18)

$$g_{pv,t}^{\text{max}} = g_{pv,t}^{\text{pre}} + p_{\text{lim}}$$

(19)

$$p_{\text{lim}} = \epsilon_{\text{allow}} C_{\text{ap}}$$

(20)

Where, $g_{pv,t}$ is the output of wind turbine at time $t$; And $g_{pv,t}^{\text{min}}$, $g_{pv,t}^{\text{max}}$ are respectively the lower limit and upper limit of wind turbine output at time $t$; $g_{pv,t}^{\text{pre}}$ is the predicted power of pv unit at time $t$; $p_{\text{lim}}$ is the output fluctuation limit of photovoltaic units; $\epsilon_{\text{allow}}$ is the allowable percentage of predicted power error; $C_{\text{ap}}$ is the installed photovoltaic capacity.

Energy storage capacity and charge-discharge constraints

$$S_{OC,t+1} = S_{OC,t}(1 - \sigma_{es}) - (\eta_{es,c} I_{es,c} P_{es,c} + \frac{1}{\eta_{es,d}} I_{es,d} P_{es,d}) \Delta t - \frac{1}{C_{es,cap}}$$

(21)

$$S_{OC,\text{min}} \leq S_{OC,t+1} \leq S_{OC,\text{max}}$$

(22)

Where, $S_{OC,t+1}$, $S_{OC,t}$ are respectively the charged states (before and after charging and discharging) of energy storage devices in time $t+1$ and $t$, and $S_{OC,\text{min}}$, $S_{OC,\text{max}}$ are the lower limit and upper limit of the charged states of energy storage devices. $\sigma_{es}$ is the self-discharge rate; And $\eta_{es,c}$, $\eta_{es,d}$ are the charging and discharging efficiency of energy storage devices, and $I_{es,c}$, $I_{es,d}$ are the charging and discharging state variables of energy storage devices respectively, $P_{es,c}$ and $P_{es,d}$ are 0-1 variables.

$$I_{es,c} P_{es,c,\text{min}} + I_{es,d} P_{es,d,\text{min}} \leq P_{y}$$

(23)

$$P_{y} \leq I_{es,c} P_{es,c,\text{max}} + I_{es,d} P_{es,d,\text{max}}$$

(24)
Where, \( P_{es,c,\text{min}} \), \( P_{es,d,\text{min}} \), \( P_{es,c,\text{max}} \), \( P_{es,d,\text{max}} \) and are the minimum, maximum charging and discharging powers of energy storage devices respectively; \( y \) is \( es, c \) or \( es, d \).

Photothermal capacity

\[
Q_{SC}(t) = F_{\text{solar}}(t) \cdot \eta_{\text{solar,SC}}
\]

\[
Q_{SC}(t) = Q_{SC,\text{in}}(t) + Q_{SC,\text{HE}}(t)
\]

Where, \( Q_{SC}(t) \) is the actual heat collected by the solar collector at time \( t \), \( \eta_{\text{solar,SC}} \) is the heat conversion efficiency of the solar collector at time \( t \), and \( Q_{SC,\text{in}}(t) \) and \( Q_{SC,\text{HE}}(t) \) respectively represents the heat generated by SC at time \( t \) for heat storage tank and heating switch.

System reserve constraint

\[
(g_{\text{ess},t} - g_{\text{ESS}}) + (g_{\text{CSP},t} - g_{\text{CSP}}) \geq r_1 \cdot L + r_2 \cdot g_{\text{wind},t} + r_3 \cdot g_{\text{solar},t}
\]

\[
(g_{\text{ESS},t} - g_{\text{min},t}) + (g_{\text{CSP},t} - g_{\text{min},t}) \geq r_4 \cdot g_{\text{wind},t} + r_5 \cdot g_{\text{solar},t}
\]

Where, \( g_{\text{max},t} \) and \( g_{\text{max},t} \) respectively energy storage system and thermal units at time \( t \) of the maximum output power, \( g_{\text{min},t} \) and \( g_{\text{min},t} \) respectively energy storage system and heat sets the minimum output power at time \( t \), \( r_1 \), \( r_2 \) and \( r_3 \) are respectively load, the spinning reserve on the coefficient of wind power and photovoltaic power generation, \( r_4 \) and \( r_5 \) are respectively the spinning reserve coefficient of wind power and photovoltaic power generation.

FM market constraints

\[
0 \leq \Delta t \leq T - 2
\]

\[
P_{\text{d,\text{min}}} \leq P_{\text{d,E}} \leq P_{\text{d,\text{max}}} / P_{\text{c,\text{min}}} \leq P_{\text{c,E}} \leq P_{\text{c,\text{max}}}
\]

\[
SOC_{\text{min}} \leq SOC \leq SOC_{\text{max}}
\]

Where, subscript \( d \) represents the discharge of the energy storage system, subscript \( c \) represents the charge of the energy storage system, \( P_{\text{c,\text{max}}} \) and \( P_{\text{c,\text{min}}} \) represents the power limit (unit MW) in the charge and discharge state of the energy storage system, \( SOC \) represents the charged state of the energy storage system, \( SOC_{\text{max}} \) and \( SOC_{\text{min}} \) represent the limit value of the charged state of the energy storage system.

The calculation formula of \( SOC \) is:

\[
SOC = SOC_{S} - (0.5(P_{\text{ref}} + P_{\text{c}})\Delta t) + 2P_{\text{ref}} + P_{\text{c}}(T - 2 - \Delta t)) / Q_{N}
\]

Where, \( SOC_{S} \) represents the state of charge of the energy storage system at time \( t_S \), \( P_{\text{ref}} \) is the regulatory instruction value (unit is MW) sent to the unit during this period. For FM energy storage power station, \( P_{N}, \Delta P_{N}, Q_{N}, v_{N}, t_{N} \) and \( P_{\text{AGC}}^{\text{ESS}} \) are known parameters. \( v_{N} \) represents the standard regulating rate of the unit (unit), \( P_{N} \) represents the rated power of the FM unit (unit: MW), \( Q_{N} \) represents the rated capacity of the energy storage system (unit: MW·s), and \( \Delta P_{N} \) represents the allowable adjustment deviation of the unit (unit: MW).

Peak regulation market constraints

\[
\sum_{j=1}^{M} \beta_{j} P_{\text{ESS,j}}^{\text{FR}} + \sum_{l=1}^{L} \alpha_{l} P_{\text{CSP,l}}^{\text{FR}} \geq P_{\text{FR}}
\]
$$\sum_{j=1}^{M} U_{\text{task}}^{\text{ESS}} + \sum_{l=1}^{L} U_{\text{task}}^{\text{CSP}} \geq U_{FR} \quad (34)$$

$$P_{\text{min}}^{\text{ESS}} \leq P_{\text{max}}^{\text{ESS}} \leq P_{\text{max}}^{\text{ESS}} \quad j = 1 \ldots M \quad (35)$$

$$P_{\text{min}}^{\text{CSP}} \leq P_{\text{max}}^{\text{CSP}} \leq P_{\text{max}}^{\text{CSP}} \quad l = 1 \ldots L \quad (36)$$

Where, M and L respectively load of available energy storage power supply quantity and peak shaving of field power supply quantity, j refers to the energy storage of unit j, l refers to the thermal unit of unit l, $P_{\text{ESS}}^{j}$ refers to the energy storage in load capacity, $P_{\text{CSP}}^{l}$ refers to the load capacity of field, $P_{FR}$ refers to the next peak shaving capacity requirements, $\beta_j$ refers to the adjustable capacity adjustment coefficient of energy storage of unit j, $\alpha_l$ refers to the adjustable capacity adjustment coefficient of thermal unit of unit l, $U_{\text{task}}^{\text{ESS}}$ refers to energy storage amount of the expected peak shaving task (in MW) of unit j, $U_{\text{task}}^{\text{CSP}}$ refers to the solar-thermal complete expected peakload quota (in MW) of unit l, $U_{FR}$ refers to the total system FM quota requirements (in MW), $P_{\text{min}}^{\text{ESS}}$ represents the minimum adjustable capacity of energy storage of the unit j, $P_{\text{max}}^{\text{ESS}}$ represents the maximum adjustable capacity of energy storage of the unit j, $U_{\text{task}}^{\text{CSP}}$ represents the minimum adjustable capacity of light and heat of the unit l, $P_{\text{min}}^{\text{CSP}}$ and $P_{\text{max}}^{\text{CSP}}$ represents the maximum adjustable capacity of light and heat of the unit l.

3. Empirical analysis

3.1. Analysis of electricity trading strategy and income.

The data of government subsidies, desulfurization price and cost of wind power and photovoltaic power are shown in Table 1. The timing sequence curves of output power of a certain wind farm and photovoltaic power field in northwest China are shown in Figure 1 and 2.

**Table 1. Wind power and photovoltaic cost data unit (yuan/kW·h)**

| $C_{TL}$ | $C_{\text{subsidy}}$ | $C_{\text{cost}}$ | $C_{\text{subsidy}}$ | $C_{\text{2}}$ |
|---------|---------------------|------------------|---------------------|-----------|
| 0.4     | 0.3                 | 0.34             | 0.4                 | 0.72      |

$$R_{\text{wind}} = (C_{TL} + C_{\text{subsidy}} - C_{\text{cost}}) \quad P_{\text{wind}} = 0.36 P_{\text{wind}} \quad (37)$$

$$R_{\text{solar}} = (C_{TL} + C_{\text{subsidy}} - C_{\text{2}}) \quad P_{\text{solar}} = 0.08 P_{\text{solar}} \quad (38)$$

**Fig. 1** Hourly generation curve of wind farm within a year
According to the above data, the revenue from the joint participation of wind power and photovoltaic in electricity transaction is 12.651 billion yuan.

3.2. Energy storage participates in strategy and benefit analysis of peak regulation and frequency modulation.

(1) Strategy and benefit analysis of energy storage participating in peak regulation.

Energy storage participating in deep peak regulation refers to the paid peak regulation auxiliary service provided when the peak regulation rate is greater than 48%, that is, the output is less than 52%. According to the difference of the energy storage peak regulation rate, the stepped compensation of thermal power units providing in-depth peak regulation auxiliary service is conducted. The compensation price range and the compensation quotation range of each range are shown in Table 2.

**Table 2.** The depth peak adjustment compensation service step by step compensation grading and each level quotation

| Level | Plant peak regulating rate (%) | Load rate (%) | Lower limit of offer (yuan/kWh) | Upper limit of offer (yuan/kWh) |
|-------|-------------------------------|---------------|----------------------------------|--------------------------------|
| 1     | (48, 55)                      | (45, 52)      | 0                                | 0.4                            |
| 2     | (55, 60)                      | (40, 45)      | 0.4                              | 0.6                            |
| 3     | (60, 100)                     | (0, 40)       | 0.6                              | 0.8                            |

The energy storage system submits the next day's deep peak adjustment compensation quotation to the dispatching institution under its jurisdiction every day, and the quotation can float voluntarily within the quotation range of each file. The dispatching institution under its jurisdiction sorts the quotation in the order from low to high, and takes the ranking result as the basis of deep peak adjustment and dispatching. The highest quotation of the depth peak adjustment service actually occurred within the unit statistics period on the same day is the clearing price of each file, which is taken as the settlement price.

$$R_{ESS2} = \sum_{i=1}^{3} Q_{ESS}^{i} p_{pi} = 0.4Q_{1}^{ESS} + 0.6Q_{2}^{ESS} + 0.8Q_{3}^{ESS}$$  \hspace{1cm} (39)$$

In order to maximize the energy storage peak-regulation benefit $R_{ESS2}$, it is necessary to apply the full capacity of the energy storage battery to the paid auxiliary service of the third grade deep peak-regulation, that is, $Q_{1}^{ESS} = Q_{2}^{ESS} = 0$, and select units with peak-regulation rate of 60% or above to provide deep peak-regulation service. For example, a 50MW, 15-minute battery energy storage peaking
system is selected for calculation. According to formula (40), the compensation income of a peaking adjustment of energy storage battery is 24,000 yuan.

Strategy and benefit analysis of energy storage participating in frequency modulation

The 50MW, 15-minute energy storage frequency modulation system of lithium iron phosphate battery provided by a domestic lithium battery manufacturer is selected as the test example. Its parameters are shown in table 3. The battery cost is 3500 yuan/kWh, the energy storage system inverter cost and the power station construction cost are 1500 yuan/kW. The operating environment temperature of the energy storage battery is 25°C.

**Table 3. Parameters of battery energy storage frequency modulation system**

| Parameter/unit | Parameter values | Parameter/unit | Parameter values |
|----------------|------------------|----------------|------------------|
| P_N/ MW        | 32               | P_cmax/ MW     | 32               |
| Q_N/ MWh       | 8                | P_cmin/ MW     | 0                |
| P_dmax/ MW     | 32               | SOCmax         | 0.95             |
| P_dmin/ MW     | 0                | SOCmin         | 0.25             |

The parameters of the battery energy storage system involved in FM compensation calculation are as follows:

\[ v_N = 1.5\% \times P_N \text{ MW/min} \]
\[ \Delta P_N = 1\% \times P_N \text{ MW} \]
\[ t_N = 30s \]
\[ P_{AGC}^{ESS} = 15\text{ yuan/MW} \]

The characteristic parameters of the life model of energy storage system are as follows:

\[ a=4.966 \times 10^4 \]
\[ b=-14.3 \]
\[ c=3.428 \times 10^4 \]
\[ d=-2.182 \]

Where, a, b, c and d are the characteristic parameters of the life equation of the energy storage system, which can be obtained according to the measured data provided by the battery manufacturer.

Using the net income maximization model, time series simulation is carried out based on the typical frequency modulation instruction issued by the power grid at a certain time of day. The local simulation results are shown in Figure 3. The energy storage frequency modulation system can quickly respond to AGC instructions and optimize control according to its own net profit maximization control strategy.

Before receiving instructions, \( P_S = 0 \), \( SOC_S = 0.75 \).

**Fig. 3** The simulation results were enlarged locally

The actual simulation data shown in Figure 3 is shown in Table 4.
Table 4. The simulation data of Figure 3

| $P_{ref}/MW$ | T/s | $P_E/MW$ | $\Delta T$/S | Net income/yuan |
|--------------|-----|----------|--------------|----------------|
| -13.2        | 10  | -13.2    | 8            | 646.1          |
| -5.5         | 27  | -5.5     | 0            | -289.7         |
| -9.7         | 25  | -9.7     | 0            | 185.6          |
| 13.6         | 150 | 13.6     | 148          | 535.5          |
| 6.6          | 27  | 6.6      | 0            | -166.8         |
| 10           | 13  | 10       | 0            | 255.8          |
| 12           | 17  | 12       | 0            | 473.4          |
| -8.7         | 39  | -8.7     | 32.8         | 123.2          |
| 15.1         | 31  | 15.1     | 29           | 849.4          |
| -2.2         | 8   | 0        | NaN          | -153.6         |
| -4.4         | 12  | 0        | NaN          | -230.4         |
| -8.2         | 29  | -8.2     | 27           | 10.7           |
| 19.7         | 50  | 19.7     | 48           | 1325.2         |
| -2.4         | 13  | 0        | NaN          | -249.6         |
| -0.6         | 36  | 0        | NaN          | -691.2         |
| -13          | 54  | -13      | 52           | 486.1          |
| -12          | 28  | -12      | 0            | 432.6          |
| 2.9          | 19  | 0        | NaN          | -364.8         |
| -22.2        | 60  | -22.2    | 58           | 1478.6         |
| 11.5         | 52  | 11.5     | 35.5         | 461.1          |
| 9.5          | 25  | 9.5      | 0            | 163.1          |
| 13.1         | 31  | 13.1     | 0            | 542.5          |
| 2.9          | 32  | 2.9      | 0            | -585           |
| 18.1         | 34  | 18.1     | 32           | 1110.7         |
| -30.9        | 120 | -30.9    | 18           | 2461.3         |

Typical processes are analyzed in combination with table 4 and figure 3:

1) When the energy storage system receives the frequency modulation instruction -13.2 mw, it does not immediately follow the frequency modulation instruction to jump, but climbs from 0 MW (the initial state of the energy storage system before the simulation) to -13.2 mw through 8 s according to its own optimization results, at this time, the net income is 646.1 yuan. If the energy storage system directly follows the FM instruction to rapidly change the output to -13.2 MW, the net income will be 639 yuan.

2) When the FM command jumps from -13.2 mw to -5.5 mw, the battery energy storage system moves quickly after optimized control and changes its output to -5.5 mw. At this time, the energy storage system loses 289.7 yuan. If the energy storage system does not respond to the frequency modulation, the calculated energy storage system will be fined 518.4 yuan for not responding to the frequency modulation command.

3) When the frequency modulation command is switched from 15.1 mw to -2.2 mw, the energy storage system chooses not to exert power after optimized control, and bears the penalty of 153.6 yuan for the grid's failure to respond to the frequency modulation command. If continue to track the frequency modulation instruction, after calculation, the system will lose 646.6 yuan.

4) Other optimization results represent that the energy storage system will immediately respond and adjust the energy storage output to the instruction value after receiving the frequency modulation instruction. The more net income the battery energy storage system gets from frequency modulation.

To sum up, it is not difficult to see that the energy storage system can converge to the maximum point of net income after optimal control, which verifies the correctness and effectiveness of the model and algorithm proposed in this paper.

After the implementation of the electricity transmission and distribution reform, the regulator becomes the decision maker of the investment scale of the power supply company, but the regulator cannot know the power supply company better than the power supply company itself. The investment
scale optimization thinking of power Supply Company constructed in this paper is shown in figure 1. The dotted line linear causal connection line is established. The planned investment scale of power Supply Company is connected with the permitted investment scale. Take the initiative to implement the investment scale optimization strategy of power supply company under the guidance of seeking reasonable investment scale; Actively exchange information with regulators to reconcile the contradiction between the permitted investment scale and the planned investment scale of the power supply company, so as to make the final permitted investment scale approach to a reasonable investment scale, and then improve the economic and social benefits of the power supply company's investment.

3.3. Light and heat participate in the strategy and benefit analysis of peak regulation and frequency modulation

The parameters of 50MW solar thermal power station used in the calculation example are shown in Table 5. The predicted power of photovoltaic power generation and wind power generation and the predicted load values of 24 hours of typical dispatching day are shown in Figure 5.

| Parameters                                                                 | Values  |
|----------------------------------------------------------------------------|---------|
| Rated output of photothermal power station /MW                             | 500     |
| Minimum output power of photothermal power station /MW                     | 10      |
| Maximum slope climbing rate of power plant output / (MW·h⁻¹)               | 40      |
| Heat loss rate of heat storage system /%                                   | 3       |
| Thermoelectric conversion efficiency of photothermal power station /%      | 45      |
| Cost factor of heating and power generation for heat collector / (yuan·MWh⁻¹) | 20      |
| Cost factor of heat storage unit for heating and power generation / (yuan·MWh⁻¹) | 40      |
| Maximum daily heat storage capacity of heat storage system /MWh            | 1000    |
| Initial value of heat storage capacity of heat storage system /MWh          | 400     |
| Lower limit of heat storage system /MWh                                    | 100     |

Fig. 4 Grid load, wind power and pv power forecast power

The numerical values in the calculation process are set as follows: load prediction error rate : \(L = 15\%\), prediction error rate for wind power, photovoltaic and photovoltaic power generation: \(F = G = R = 5\%\), system reserve cost coefficient: \(k_r = 112\text{yuan/MW}\), and peak load capacity cost coefficient: \(k_p = 231\text{yuan/MW}\)
Table 6. Investment simulation model of power supply company (Unit: MW)

| Moment | Network load \( P_{Lt} \) | Wind power \( P_{Lf} \) | Photovoltaic \( P_{gt} \) | Optothermal \( P_{Gt} \) |
|--------|--------------------------|-----------------|-----------------|-----------------|
| 0      | 225                      | 75              | 0               | 25              |
| 1      | 230                      | 90              | 0               | 42              |
| 2      | 230                      | 80              | 0               | 12              |
| 3      | 231                      | 55              | 0               | 15              |
| 4      | 200                      | 60              | 0               | 20              |
| 5      | 220                      | 56              | 0               | 10              |
| 6      | 210                      | 57              | 25              | 12              |
| 7      | 225                      | 70              | 50              | 10              |
| 8      | 250                      | 75              | 55              | 21              |
| 9      | 260                      | 73              | 70              | 59              |
| 10     | 300                      | 69              | 100             | 69              |
| 11     | 290                      | 60              | 105             | 43              |
| 12     | 240                      | 61              | 110             | 23              |
| 13     | 230                      | 59              | 109             | 10              |
| 14     | 240                      | 55              | 90              | 47              |
| 15     | 245                      | 70              | 80              | 48              |
| 16     | 250                      | 80              | 60              | 90              |
| 17     | 275                      | 79              | 30              | 49              |
| 18     | 300                      | 65              | 0               | 40              |
| 19     | 290                      | 60              | 0               | 30              |
| 20     | 270                      | 50              | 0               | 10              |
| 21     | 260                      | 80              | 0               | 12              |
| 22     | 255                      | 90              | 0               | 11              |
| 23     | 240                      | 40              | 0               | 50              |

According to equations (11) - (13), it can be concluded that the reserve income of the solar thermal power station in this adjustment is 118,434 yuan, and the peak adjustment income is 627,165 yuan.

4. Conclusions and recommendations

According to the above analysis, the operation modes of the multi-energy complementary new energy generation system participating in the operation of the power generation market, frequency modulation, peak regulation and standby market are various. By establishing the mathematical model of operation objective function and operation constraint conditions, the operation strategy of wind-scenery heat storage participating in auxiliary service market can be optimized, which indicates that participation of multi-energy complementary new energy generation system in the auxiliary power market is beneficial to increase revenue and optimize the operation structure of the market.

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