Capacity configuration optimization and analysis for multi-energy complementary microgrid in hydropower station considering the renewable energy accommodation

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Abstract—Aiming at the problems of large short-term fluctuation, strong randomness and difficulty to consume of renewable energy generation, it is an important way to integrate abundant wind and photovoltaic (PV) power into hydropower stations to promote the consumption of renewable energy sources (RES). A hydro-wind-PV and energy storage multi-energy complementary microgrid (MECM) model is proposed to meet the demand of load supply and RES consumption. Firstly, according to the characteristics of load and resource endowment, the MECM is established in a hydropower station. Secondly, according to the two different objectives of load self-sufficiency and RES consumption, the mathematical model for the capacity configuration optimization of MECM was proposed. Finally, combined with the practical case study, the effectiveness and practicability of this scheme are verified, and different configuration schemes are discussed based on different objectives.

1. Introduction
The traditional hydropower stations only have hydropower as a single form of energy supply [1]. Energy supply varies with weather conditions and seasons [2]. Therefore, WT and PV can be introduced into traditional hydropower stations. The regulation ability of hydropower can overcome the intermittent and unstable disadvantages of WT and PV power output [3-4].

At present, many scholars combine hydropower, WT and PV power to establish a MECM model with hydropower as the main part on the power generation side [5-8]. However, they did not consider the linkage with the load side. With the increasing demand of local load and the emergence of new-type loads, provided a new solution for the consumption of RES [9], considering the linkage with the load side can effectively solve the problem of RES consumption.

In this paper, with a study on the output characteristic and complementary relationship of the hydro, wind and PV, a capacity configuration optimization method of MECM is proposed, which takes the load self-sufficiency and RES consumption as the objective function. Using hydro-wind-PV coordinated operations to achieve RES complement each other, the introduction of pumped storage
increases power supply reliability, access to the EV, data center and other new-type loads increase the local consumption ability of RES.

2. System structure and analysis of energy supply mode of MECM

2.1. System structure of MECM
The MECM system designed is shown in Fig. 1, which takes hydropower as the main part and is composed of WT, PV, pumped storage, EV charging station, data center and other parts.

2.2. Operation characteristics and operation mode analysis of MECM
The energy supply mode of the MECM is mainly hydro, WT and PV complementary operation, supplemented by peak-cutting and valley-filling of pumped storage [10]. According to the load characteristics and the output characteristics of RES, the whole day can be divided into three periods.

(1) 1:00-12:00 time period: the output of PV and hydropower units increases continuously, while the output of WT increases first and then decreases. The total output power of RES is high, and the load demand is low. Prioritize WT and PV power supply, and then hydropower is used to supply the remaining load, and the power is stored by pumped storage.

(2) 12:00-19:00 time period: the output of PV and hydropower is decreasing, and the output of WT is low. The total RES output is low, but the load demand is high. Prioritize WT and PV power supply, and then hydropower is used to supply load, the pumped storage generates and EVs discharge to meet the remaining load. If the load demand is still unable to meet, electricity can be purchased from grid.

(3) 19:00-24:00 time period: the energy supply mode of this period is the same as that of the 1:00-12:00 time period, but due to the higher load during this period, RES abandonment is relatively small.

3. Methodology
According to the system structure of MECM and the analysis of system operation characteristics, the equipment model is constructed, and the objective function and constraints are set for the two objectives of load self-sufficiency and RES consumption, in which evaluation index are listed to evaluate the economy and effectiveness of the two schemes finally.

3.1. Equipment model
(1) Power generation equipment model
The main generating equipment of MECM is hydraulic generator, WT and PV. The model of three generating equipment is showed as follows:

\[ P_{by} = 9.81 \eta_{by} Q_d H_d \]  \hspace{1cm} (1)

\[ P_w = \begin{cases} 
0 & \text{if } v < v_{ci}, v \geq v_{co} \\
\frac{P_R}{v_R - v_{ci}} v^3 - \frac{P_R}{v_R - v_{ci}} v_{ci}^3 & \text{if } v_{ci} \leq v < v_R \\
\frac{P_R}{v_R - v_{ci}} v^3 - \frac{P_R}{v_R - v_{ci}} v_{ci}^3 & \text{if } v_R \leq v < v_{co} 
\end{cases} \]  \hspace{1cm} (2)

\[ P_{pv} = \alpha I_r \]  \hspace{1cm} (3)

Where, \( P_{by} \) is the output power of the turbine; \( H_d \) is the design head; \( Q_d \) is power generation discharge; \( \eta_{by} \) is the efficiency of hydraulic turbine, which is 0.9; \( P_{pv} \) is output power, \( I_r \) is irradiation intensity, and \( \alpha \) is the conversion coefficient of PV power; \( P_w \) is the output power of the WT; \( v \) is the actual wind speed of the WT; \( v_{ci}, v_{co} \) and \( v_R \) are respectively the cut to the wind speed, cut out of the wind speed and rated wind speed of the WT. \( P_R \) is the rated power of the WT.

2) Storage model

The water volume of the upper reservoir after storage and discharge of the pumped storage power station is expressed as follows:

\[ W(t+1) = W(t) + \frac{3600 \times 1000 \eta_{up} P_{up}(t)}{\rho g H} - \frac{3600 \times 1000 P_{pv}(t)}{\eta_h \eta_{up} \rho g H} \]  \hspace{1cm} (4)

Where, \( W(t) \) is the remaining water of the reservoir at the time \( t \); \( \eta_h \) and \( \eta_b \) are respectively the pumping efficiency and power generation efficiency of the hydro-generator set, taking 80% and 90% respectively; \( \eta_{up} \) is pipeline efficiency, which is 95%; \( P_{pv}(t) \) and \( P_{by}(t) \) are respectively the pumping power and power generation power of the hydro-generator set; \( H \) is head height;

3.2. Configuring the objective functions of optimization

Objective 1 is that the load is mainly supplied by MECMs, and the purchase of electricity from large power grids is minimized. Objective 2 is that the MECM system can fully consume its own renewable energy generation, and the power abandonment is minimized.

\[ \min F_{dj} = \min \sum_{t=1}^{24} P_b(t) \]  \hspace{1cm} (5)

\[ \min F_{loss} = \min \sum_{t=1}^{24} P_{loss}(t) \]  \hspace{1cm} (6)

Where, \( P_b(t) \) is the power purchased from the power grid; \( P_{loss}(t) \) is power abandonment.

3.3. Configuring the constraints of the optimization

The constraint conditions are as follows: Eq. 7 and Eq. 8 are power constraints, Eq. 9 and Eq. 10 are water flow constraints, and Eq. 11 and Eq. 12 are EV charge and discharge constraints.

\[ P_{by}(t) + P_w(t) + P_{pv}(t) + P_{ev}(t) + P_{p}(t) = P_L(t) + P_{ev}(t) + P_{pv}(t) + P_{loss}(t) \]  \hspace{1cm} (7)

\[ P_{i,\text{min}} \leq P_i(t) \leq P_{i,\text{max}} \]  \hspace{1cm} (8)

\[ V_{cap,\text{min}} \leq W(t) \leq V_{cap,\text{max}} \]  \hspace{1cm} (9)

\[ W(\text{start}) = W(\text{end}) \]  \hspace{1cm} (10)

\[ E_{i,\text{min}} \leq P_{ev}(t) \leq E_{i,\text{max}} \]  \hspace{1cm} (11)

\[ E_{f,\text{min}} \leq P_{ef}(t) \leq E_{f,\text{max}} \]  \hspace{1cm} (12)
Where, \( P_l(t) \), \( P_p(t) \) and \( P_{pv}(t) \) are respectively the power that the wind power supplies to the local load, pumped storage pumping and EV at time \( t \); \( P_{l,\text{min}} \) indicates the lower limit of output power; \( P_{l,\text{max}} \) indicates the upper limit of output power; \( V_{cap,\text{min}} \) is the lower limit of water storage capacity; \( V_{cap,\text{max}} \) is the upper limit of water storage capacity; \( E_{c,\text{max}} \) and \( E_{c,\text{min}} \) are the maximum and minimum value of EV charge. \( E_{f,\text{max}} \) and \( E_{f,\text{min}} \) are the maximum and minimum value of EV discharge.

### 3.4. Evaluation index

Self-sufficiency rate refers to the percentage of station power load and local load supplied by hydropower stations in total load. The power abandonment rate is equal to the power abandonment divided by the total generation of RES. The cost of MECM configuration for hydropower station can be divided into investment cost \( (C_{ic}) \) and operation and maintenance cost \( (C_{om}) \).

\[
L_{sj} = \frac{\sum_{t=1}^{24} P_{hy}(t) + P_w(t) + P_{pv}(t)}{\sum_{t=1}^{24} P_l(t) + P_c(t)}
\]  

(13)

\[
L_{loss} = \frac{\sum_{t=1}^{24} P_{loss}(t)}{\sum_{t=1}^{24} P_{hy}(t) + P_w(t) + P_{pv}(t)}
\]  

(14)

\[
C_{ic} = C_w N_w + C_{pv} N_{pv} + C_{cap} N_{cap}
\]

\[
C_{om} = C_{om,\text{hy}} N_{hy} + C_{om,\text{w}} N_w + C_{om,\text{pv}} N_{pv} + C_{om,\text{cap}} N_{cap} + P_{grid}
\]  

(15)

Where, \( P(t) \) is the station power load; \( C_w, C_{pv}, C_{cap} \) are the unit prices of each unit of WT, PV, pumped storage respectively; \( C_{om,\text{hy}}, C_{om,\text{w}}, C_{om,\text{pv}}, C_{om,\text{cap}} \) are the operation and maintenance costs of hydraulic turbine, WT, PV, pumped storage unit; \( N_{hy}, N_w, N_{pv}, N_{cap} \) are the unit capacity of hydraulic turbine, WT, PV, pumped storage unit; \( C_{grid} \) is the electric price purchased from the grid.

### 4. Case study

This study takes a hydropower station in China as a case, which contains two 1250kW hydroelectric generating units and a reservoir of 4000 m³. The load demand and the typical daily hydro, WT and PV output per kW capacity as shown in Fig. 2. The power purchase cost of the MECM system is 0.54 CNY/kWh. Related parameters of other equipment are shown in the following table1.

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Table 1: Equipment price parameters

| Equipment                     | Construction cost (CNY/kW) | Operation and maintenance cost (CNY/kW) | Life cycle (Years) |
|-------------------------------|-----------------------------|----------------------------------------|-------------------|
| WT                            | 1695                        | 51                                     | 20                |
| PV                            | 1040                        | 9                                      | 25                |
| Reversible pump turbine       | 2100                        | 21                                     | 15                |

5. Result Analysis and Discussion

The configuration capacity calculated under the two conditions of energy self-sufficiency and complete local consumption is shown in Tab. 2: Scheme 1 is that loads are supplied as far as possible by MECM; Scheme 2 is to reduce more renewable energy power abandonment of MECM.

Table 2: Configuration optimization results

| Equipment          | Scheme 1: Capacity (%) | Scheme 2: Capacity (%) |
|--------------------|------------------------|------------------------|
| Hydropower Unit    | 39.16                  | 49.54                  |
| WT                 | 24.05                  | 18.90                  |
| PV                 | 33.92                  | 25.77                  |
| Pumped storage     | 2.87                   | 5.78                   |

As shown in Tab. 2, in order to reduce power purchase from the power grid, improve the self-sufficiency rate, newly configured WT and PV capacities account for 59.68% of total generating units’ capacity. In order to reduce RES power abandonment, the configured WT and PV capacities are relatively small, accounting for 47.42% of the total generating unit capacity. In addition, in order to further reduce power abandonment of RES, more capacity of pumped storage is configured.

Table 3: Performance evaluation analysis of configuration optimization

| Scheme | Investment cost (CNY/D) | Operational cost (CNY/D) | Total cost (CNY/D) | Self-sufficiency rate (%) | Power abandonment rate (%) |
|--------|--------------------------|--------------------------|--------------------|---------------------------|----------------------------|
| 1      | 1111.4                   | 890.88                   | 2002.3             | 98.48                     | 14.95                      |
| 2      | 780.11                   | 1816.5                   | 2596.6             | 94.29                     | 1.83                       |

As shown in Tab. 3, increasing self-sufficiency rate requires configuration of more RES, the investment cost is relatively high and power abandonment account for 14.95% of the total generated energy. To reduce power abandonment of RES, MECM only supplies 94.29% of the load. Compared to scheme 1, more electricity needs to be purchased from the grid, resulting in higher operating costs.

As shown in Fig. 3, scheme 1 has massive power abandonment at 1:00-12:00. Due to the small renewable energy generation and large load at 17:00-19:00, it is necessary to purchase electricity to

(a) Scheme 1: self-sufficient
(b) Scheme 2: complete consumption

Fig.3 Power output of equipment under two configuration objectives
maintain the balance between supply and demand. In scheme 2, only a small amount of electricity was abandoned at 6:00, 22:00 and 23:00. However, due to the capacity of RES configuration is small, more electricity power would be necessary to be purchased from the grid at 14:00-19:00.

6. Conclusion
In order to improve the RES utilization and power supply reliability, this paper establishes a mathematical model of MECM. According to different optimization objectives of MECM, two different capacity configuration schemes are proposed respectively. Based on the results and discussions presented above, the conclusions are obtained as below:

1) Under the two configurations, the MECM has effectively played the complementary advantages of the three RES and improved the reliability of energy supply while maintaining stable operation.

2) Access to new-type loads can effectively increase the utilization rate of RES and improve the reliability of the energy supply.

In the future work, the influence of multiple climate conditions on the optimal configuration of MECM will be considered.

Acknowledgments
This work was financially supported by the Science and Technology Project of State Grid Sichuan Electric Power Company (2021kjc07051515).

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