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Risk Analysis Method of Cascade Plants Operation in Medium Term Based on Multi-Scale Market and Settlement Rules

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ABSTRACT Due to the distribution of runoff is uneven and uncertain in time and space, there are huge differences between the electricity markets dominated by hydropower and thermal power. Therefore, how to evaluate the risk of cascade plants participating in electricity market is an urgent problem to be solved. Based on the rules of the market in southwest China which hydropower plays a leading role, this paper proposes a risk analysis method for cascade hydropower to participate in market which is coupled with monthly market and day-ahead market: Copula-Monet Carlo is used to generate the combined scenario of daily runoff and daily clearing price, and the LINGO solver is used to calculate the generation income of all scenarios, and the corresponding conditional value-at-risk value(CVaR) of portfolio is obtained according to the confidence level. The method takes into account the uncertainty of runoff and electricity price in the meantime, as well as the settlement order and deviation assessment of each market in the settlement rules, and can directly solve the income and risk value. The process is simple and the physical meaning is clear. Using the actual data of a grid cascade hydropower participating in the electricity market as an example, the simulation analysis of the results shows that the proposed method can easily solve the portfolio risk value, and can more reasonably evaluate the risk value compared with the considering runoff and day-ahead market clearing prices separately.

INDEX TERMS Cascade hydropower plants, portfolio, settlement rules, the risk assessment.

I. INTRODUCTION

Since the new round of electricity reform in 2015, most of regions and provinces in China have established a mature and complete medium- and long-term electricity market through continuous efforts in recent years. The rich trading variety, including monthly bilateral market, continuous bidirectional market, pre- and post-contract transfer market, etc., has greatly stimulated the enthusiasm of the power supply side and the demand side to participate in electricity market. And the improved trading rules and settlement rules year by year have also ensured the performance rate of medium- and long-term trading contracts. Take Yunnan province dominated by hydropower in southwest China as example, it has already formed an electricity market pattern with ''medium- and long-term trading as main way, day-ahead market as a supplement''. According to statistics, the electricity marketization volume reached 104.538 billion kWh in 2019, an increase of 22.84% over last year. It accounts for more than 58% of the province's power generation energy, ranking first in terms of market openness in China. Of this, the hydropower marketization volume reached 83.627 billion kWh, accounting for 80%.

In the electricity market environment, each type of power plant can bid volume and price according its power generation capacity, and will be scheduled to operate on the basis of the trading contract that formed by the market clearing algorithm. Different from other power sources, such as thermal power and nuclear power, hydropower needs to take more operational risks when participating in the electricity market

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because of the non-uniformity and uncertainty of runoff distribution in time and space. Since the trading contract formed by medium- and long-term market can ensure their primary benefit, hydropower plants are likely to occur abandoned water due to the deviation of runoff prediction in the operating process. This requires the hydropower plant to participate in the short-term electricity market, such as a day-ahead market, according to the actual situation. In general, hydropower plants will take into account the deviation of runoff prediction and other emergencies, and participate in the medium- and long-term electricity market according to 70% to 80% of their capacity and the surplus capacity will be arranged to participate in the short-term market. In the meanwhile, the hydropower plant also needs to adjust the bidding intention appropriately in combination with the clearing price and settlement rules of different scales of electricity market, so as to obtain larger profits and avoid market risks. Therefore, how to evaluate these risks has become an urgent theoretical and practical challenge for hydropower plants.

For the problem of the cascade hydropower plants participating in the market, a lot of research have been carried out, mainly included two aspects: the modeling of cascade hydropower and the risk of market uncertainty. For the modeling, [7] propose a mixed integer nonlinear programming (MINLP) model for scheduling of the short-term integrated operation of a series of price-taker hydroelectric plants (H-GENCO) along a cascaded reservoir system in a pool-based electricity market is presented, taking into account technical efficiency, or to maximize technical efficiency, maintaining a profit level. Reference [8] addresses the self-scheduling of a hydro generating company in a pool-based electricity market. The objective is to maximize the profit of the company from selling energy in the day-ahead market. This paper proposes a 0/1 mixed-integer linear programming (LP) model to account, in every plant, for the nonlinear and nonconcave three dimensional relationship between the power produced, the water discharged and the head of the associated reservoir. Reference [9] describes two applications: (1) A model intended for the system of a single power company, with the power price as an exogenous stochastic variable. (2) A global model for a large system (possibly many countries) where the power price is an internal (endogenous) variable. Reference [10] consider the case when RES owners participate in a two-settlement wholesale market, and a market operator financially penalizes the deviation of real-time generation from the day-ahead contract and propose a bidding strategy called Gaussian residual bidding (GRB) to maximize the coalition gain under different price-penalty ratio in the two-settlement process. For the risk analysis, previous research has uses prospect theory, information gap decision theory [11]–[13], CVaR [14] and Markowitz mean variance model [15] to analyze transaction risk, but most of the studies are aimed at thermal power main body and are difficult to be applied to hydropower problems [16]. To provide a more useful trading strategy portfolio, they first define a group trading strategy portfolio (GTSP). Then, an algorithm that utilizes the grouping genetic algorithm is designed for solving the GTSP optimization problem. In the chromosome representation, the grouping, strategy, and weight parts are employed to encode a possible GTSP. The fitness value of a chromosome is calculated by the group balance, weight balance, portfolio return, and risk to assess the quality of every possible solution. Reference [17] considering the uncertainty of residual demand curve, proposes a stochastic MILP approach to maximize the total expected profit of a price-maker hydro generating company. Reference [18] considers gains from coordinated bidding strategies in multiple electricity markets, a comprehensive scenario-generation methodology which simulation the portfolio size is proposed, and formulate a coordinated planning problem for a hydropower producer using stochastic mixed-integer programming. Reference [19] scenario number modeling is used to consider the randomness of runoff without considering the correlation between electricity price and runoff. Table 1 shows the classification and summary of the literatures.

TABLE 1. Literature review summarize.

classification	literature	summary
modeling	[7]	A mixed integer nonlinear programming (MINLP) model for short-term scheduling of a series of price-taker hydroelectric plants
	[8]	A 0/1 mixed-integer linear programming (LP) model to maximize the profit of the company from selling energy in the day-ahead market
	[9]	1) A model with the power price as an exogenous stochastic variable; 2) A global model with the power price as an internal (endogenous) variable
	[10]	A bidding strategy to maximize the coalition gain under different price-penalty ratio in the two-settlement process.
risk of market uncertainty	[11]-[15]	Analyze transaction risk by using information gap decision theory, CVaR and Markowitz mean variance model, respectively.
	[16]	DTSP is defined and solved by the grouping genetic algorithm, whose fitness value is calculated by group balance, weight balance, portfolio return and risk to assess the quality.
	[17]	A stochastic MILP approach to maximize the total expected profit is proposed by considering the uncertainty of residual demand curve.
	[18]	A stochastic MILP approach to formulate a coordinated planning problem for a hydropower producer is proposed by considering the uncertainty of portfolio size in the multiple electricity markets
	[19]	Scenario number modeling is used to consider the randomness of runoff without the correlation between electricity price and runoff

However, the relationship between daily runoff and day-ahead market clearing price cannot be ignored, because the daily runoff directly affects the power generation energy of hydropower plants with poor regulating performance, and may also indirectly affects day-ahead market clearing price. On the other hand, the settlement rules will also affect the

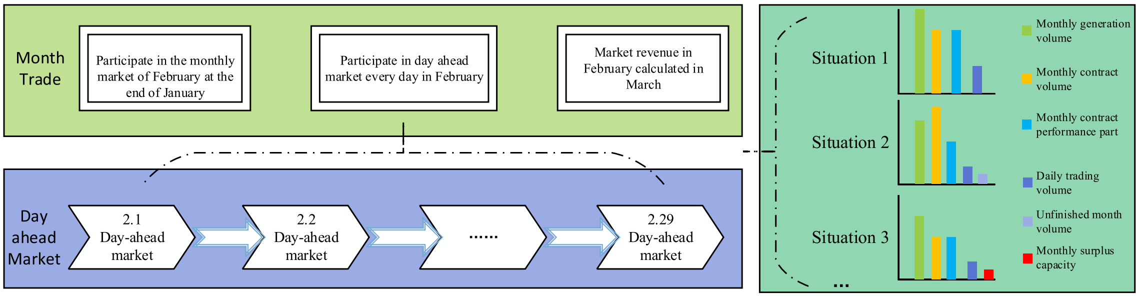


FIGURE 1. Sketch map of market structure.

benefit of hydropower plants. As far as we know, it is rare to study the dispatching operation of cascade hydropower plants considering the above two aspects under the electricity market environment.

On the basis of the above research, this paper proposes a risk analysis model of medium-term dispatching operation of cascade hydropower plants integrated into electricity market settlement rules, taking into account the uncertainty of runoff and the correlation with day-ahead market clearing price. Firstly, the structure and settlement rules of Yunnan electricity market are briefly introduced, in order to understand the problems to be considered in the operation of hydropower plant under the market environment. Secondly, the Copula-Monte Carlo method is used to generate the scenario which combination of daily runoff and day-ahead market clearing price (DMCP), which avoids the data in the scenario loss of the correlation of the original data caused by considering the uncertainty of runoff and price separately. Thirdly, lingo solver is used to obtain the power generation revenue and operation process of cascade hydropower plants according to the profit maximum model. Finally, the CVaR method is used to calculate the risk value of the portfolio, and then the results considering the electricity price and runoff separately are compared and analyzed. Taking cascade hydropower plants in Yunnan province as an example, it is verified that the proposed method and model can easily solve the risk value of transaction portfolio, and can evaluate the risk of return more reasonably than considering the price and runoff separately.

The remainder of this paper is organized as follow. The case study is presented in section 2, introduce the market structure and settlement rules. In section 3 explaining the methods of solving the model include scenario simulation, optimal operation of reservoir and risk analysis of trading portfolio. In section 4, the case study is simulated in different scenarios and its results are highlighted, before closing this work in section 5 with the main discussion.

II. MARKET STRUCTURES AND SETTLEMENT RULE

A. MONTHLY AND DAY-AHEAD MARKET

At present, the provincial electricity market in China contains different time scales. Take Yunnan as an example, including the monthly market and the day-ahead market. The monthly market is organized by Kunming Power Exchange Center (KMPEX) before the natural month, and the day-ahead market is organized in sequence in natural month. Each market will be cleared independently according to the unified clearing method to form the clearing price. For the electricity market in February 2020, the plants participate in the monthly market at the end of January and choose whether to participate in the day-ahead market according to the daily actual situation in February (this paper assume that all plants are price taker, when they quotes according to the DMCP in the day-ahead market, the declared volume can be traded). In March, according to the completion of the monthly contract and the volume of electricity traded in the day-ahead market, calculate the portfolio income of the power plant, the market structures are shown in Figure 1.

B. SETTLEMENT RULE

The settlement rules directly affect the income of power generation enterprises because of the different time scale of electricity market. According to the rules, the real on-grid power energy of power plant is firstly used for the settlement of the day-ahead market trading volume, and then the remaining part is used for the monthly trading volume. When the remaining power energy is less than the monthly trading volume, the power plant fails to complete the contract, and the unfinished part will be punished according to certain standards. On the contrary, the power plant overfulfils the contract, and the price of the excess part will be lower than the contract price.

III. MATERIALS AND METHODS

The statistical results of the provincial electricity market in China show that more than 80% of the power generation capacity of cascade hydropower plants is arranged in the monthly market to ensure the most basic revenue. In the process of day-ahead market, they often consider whether to participate to obtain more profits according to the inflow, the fluctuation of DMCP and the completion of monthly trading volume. Limited by generation capacity and settlement rules, the volume distribution between the monthly market and the day-ahead market is tightly coupled. The monthly trading results are known variables before the actual operation of each month, and the risk of monthly market income is reflected in the contract performance rate. The dynamic decision-making of the day-ahead market trading plan depends on the medium-term dispatching plan, which

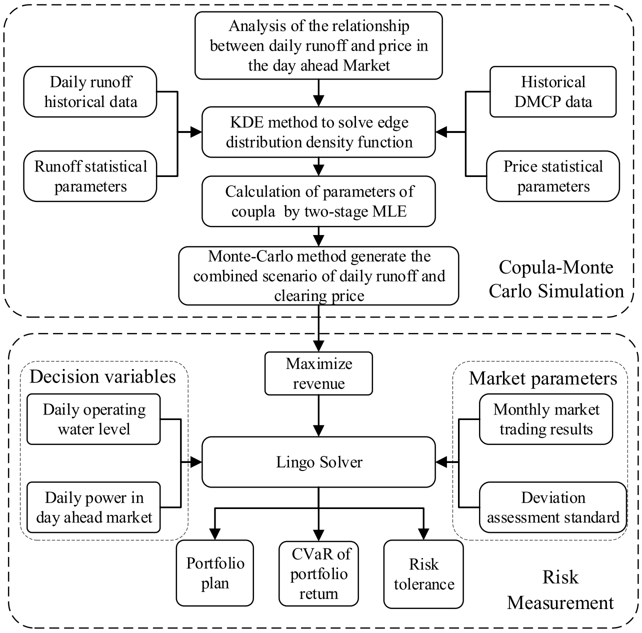


FIGURE 2. **Model framework.**

needs to bear the double risks caused by the uncertainty of daily runoff and the DMCP.

In view of the above reasons, this paper proposes an analysis method for medium-term operation risk of cascade hydropower plants under multi-scale electricity market based on settlement rules. Firstly, Copula Monte Carlo method is used to simulate the scenario which combination of daily runoff and DMCP, which avoids the data in the scenario loss of the correlation of the original data caused by considering the uncertainty of runoff and price separately. Then, lingo solver is used to calculate the portfolio income of cascade hydropower plants in each scenario; Finally, the corresponding CVaR value is obtained according to the confidence level, and the risk value of portfolio income is calculated intuitively, which can be used as a reference for cascade reservoirs to arrange their output plans and reasonably organize their participation in various transactions. The model framework is shown in Figure 2.

A. CORRELATION ANALYSIS AND MODELING OF DAILY RUNOFF AND DMCP

1) ESTIMATE THE COPULA FUNCTION

Copula theory [20]–[24] has special advantages in correlation analysis. By using copula theory, we can get a joint distribution which is closer to the actual data through the marginal distribution and a connecting function, so as to establish a more effective risk value measurement model. By copula function, the value at risk of portfolio income can be divided into two parts: the uncertainty risk of single variable and the risk of variables combination. The uncertainty risk of single variable can be completely described by their respective marginal distribution function, while the risk generated by combination can be completely described by the connecting function, which greatly simplifies the modeling problem.

Therefore, copula function can be used to describe the joint distribution of daily runoff $\{X_T\}$ and DMCP $\{Y_T\}$, $t = 1, \ldots, T$. Although the marginal distribution function of two random variables $F_X(x)$ and $G_Y(y)$ are unknown, but make sure that the marginal distribution function is a continuous function. According to Sklar's theorem, there is a unique connection function $C\,(U, V)$, which makes formula (1) valid, the specific modeling steps are as follows:

$$H(x, y) = C(u, v)(F_X(x), G_Y(y)) \tag{1}$$

Step 1: **Determining the probability density function of daily runoff and DMCP**. Although $F_X(x)$ and $G_Y(y)$ are unknown, but they can be solved by nonparametric kernel density estimation (KDE) method based on known samples to obtain probability density function. The KDE function is

$$\overset{\wedge}{f_h}(x) = \frac{1}{nh}\sum_{t=1}^{n} K(\tfrac{x-x}{h}) \tag{2}$$

where, h is it is the window width, which plays the role of smoothing curve and affects the effect of kernel density estimation. h=(4/3)1/5n-1/5, K(•) is Gaussian kernel function.

The marginal distribution function $f(x)$ can be obtained by integrating the probability density function obtained from KDE.

Step 2: **Transforming the marginal distribution function into uniform distribution.** Transform the marginal distribution functions *FX(x)* and *GY(y)* into uniform distribution *U(0,1)* by probability density functions $f(x)$ and $g(y)$. When *R ∈(0,1)*:

$$\begin{aligned} P[F(X) \le r] &= P[X \le F^{-1}(r)] \\ &= P[F^{-1}(r)] = r \Leftrightarrow F(x) = U \end{aligned} \tag{3}$$

Step 3: **Determine the parameters of copula function**. The parameter estimation of copula function generally adopts maximum likelihood estimation (MLE) and moment estimation. Because copula function itself is a distribution function, MLE method is the most commonly used parameter estimation method of copula function. The multivariate distribution function is divided into the probability density function of copula function and the density function of marginal distribution. Therefore, we use two-stage MLE method to estimate the parameters of copula function. The calculation formula is as follows:

$$\overset{\wedge}{\varphi} = \arg\max_{\varphi \in R^p} \sum_{t=1}^{T} \ln f_t(x_t; \varphi) \tag{4}$$

$$\overset{\wedge}{\gamma} = \arg\max_{\gamma \in R^q} \sum_{t=1}^{T} g_t(y_t; \gamma) \tag{5}$$

$$\overset{\wedge}{\kappa} = \arg\max_{\kappa \in R^T} \sum_{t=1}^{T} \ln c(f(x; \overset{\wedge}{\varphi}), g(y; \overset{\wedge}{\gamma})) \tag{6}$$

Step 4: **Copula function optimization**. In order to evaluate the goodness of fit of different copula functions, K-S test is used to calculate the empirical distribution of sample data and the maximum deviation of copula function distribution, and find out the copula function with the best degree of fit.

2) SIMULATED DAILY RUNOFF AND DMCP

Unlike univariate simulations, multivariate variables follow a joint distribution, so the random number cannot be generated by the marginal distribution of a variable alone, but by the joint distribution of multi variables. According to Nelson's theorem, if $u = f(x)$, $v = g(y)$, then u, v obey $U(0,1)$. As long as generating the random number $(u, v) \sim C(u, v)$, the random number (x, y) needed for the Monte-Carlo simulation can be obtained through the inverse function of marginal distribution, where $x = F^{-1}(u)$, $y = G^{-1}(v)$. The specific steps are as follows:

Step 1: Generating two independent random numbers u and w that obey the [0,1] distribution, u is the first pseudo-random number to be simulated.

Step 2: According to Nelson's theorem, Cu(v)∈[0,1] and Cu(v) obeys the uniform distribution, make Cu(v)=w, so that another pseudo-random number v:v=Cu-1(w) is obtained by the inverse function of Cu(v).

Step 3: According to the distribution functions FX(x) and GY(y) of each variable, calculate the corresponding variable values of u, v: x=F-1(u))和=G-1(v).

Step 4: Repeat steps 1-3 m times to simulate the possible scenario which combination of daily runoff and DMCP.

B. RISK ANALYSIS AND MEASUREMENT MODELING

The portfolio includes monthly market and day-ahead market. In the monthly market, the volume and price adopt the deterministic model. The day-ahead market includes the uncertainty of runoff and the risk mainly refers to the monthly contract performance failure penalty, which is closely related to the distribution weight of the portfolio and the runoff.

1) MONTHLY MARKET PROFITS MODEL

As mentioned above, the monthly electricity market is organized at the end of last month. The monthly trading price $p_{i,t}$ and the volume $e_{i,t}$ of cascade hydropower plants are the determined values. The monthly trading profits $r_{i,t}$ is:

$$r_{1,i} = p_{1,i} \times e_{1,i} \tag{7}$$

2) DAY-AHEAD MARKET PROFITS MODEL

The day ahead market profits $r_{2,i}$ is:

$$r_{2,i} = \sum_{t=1}^{T} (p_{2,t} \times e_{2,i,t}) \tag{8}$$

T is the number of days in the month, 30 days in this paper. $p_{2,t}$ is DMCP on day t. $e_{2,i,t}$ is the trading volume of plants i on day t.

3) PORTFOLIO PROFITS MODEL

According to the settlement rules, the priority of day-ahead market settlement is higher than that of monthly market. So the portfolio profits of cascade hydropower plants include monthly trading profits, day-ahead market profits and deviation assessment profits, which is expressed as

$$r = \sum_{i=1}^{I} (r_{1,i} + r_{2,i} + r_{3,i}) \tag{9}$$

$$r_{3,i} = e_{3,i} \times p_{3,i} \tag{10}$$

$$e_{3,i} = e_i - \sum_{t=1}^{T} e_{2,i} - e_{1,i} \tag{11}$$

$$p_{3,i} == \begin{cases} (1 + penalty) \times p_{1,i}, e_{3,i} < 0 \\ (1 - penalty) \times p_{1,i}, e_{3,i} > 0 \end{cases} \tag{12}$$

where, r is the portfolio profits of all plants. $r_{3,i}$ is the deviation assessment profits of plant i. e_i is the practical generating volume of plant i. $p_{3,i}$ is the deviation penalty price of plant i, when $e_{3,i}$ is less than zero, $p_{3,i}$ is the unfinish penalty price(UPP) and contrarily $p_{3,i}$ is the surpass generation price(SGP). *penalty* is the punishment standard.

4) RISK MEASUREMENT MODEL OF PORTFOLIO BASED ON CVAR

CVaR is conditional value at risk, it is a better risk measurement technology than value at risk (VaR) proposed by rockafeuar and uryasev in 1997, which means the average loss value of a portfolio when the loss of the portfolio exceeds a given var [25]–[29]. When using copula function to calculate CVaR of portfolio, the analytical formula of CVaR is not easy to solve. To facilitate the calculation, Copula Monte Carlo simulation method described in the previous chapter is used to calculate the specific value of CVaR. If the financial assets in the portfolio have been determined, then the market risk is equivalent to the risk of the asset structure in the portfolio, which can be described by a corresponding copula function, and then the empirical distribution of the future return of the portfolio can be obtained through simulation, and the CVaR value of the portfolio can be obtained for the given confidence level α.

In this paper, the joint distribution of daily runoff and DMCP is described by the marginal distribution functions $F_X(x)$, $G_Y(y)$ and a copula function. Suppose Z is the feasible set of investment, Z∈ R_n, $r(z, x, y)$ is the revenue function, $z \in Z$ is the n-dimensional combination scheme vector, x, y are the random factors of the market, the joint distribution function is expressed as $C(F_X(x), G_Y(y))$. So for the determined z, $r(z, x, y)$ is a random variable determined by x, y, the empirical distribution of R is generated by the Copula Monte Carlo method mentioned in the previous chapter, then when the portfolio is z, the corresponding VaR value of $r(z,x,y)$ at the given set credit level is calculated by:

$$p(r \leq VaR) = \alpha \tag{13}$$

Furthermore, CVaR, a conditional risk measure with a probability of portfolio exceeding a certain threshold, can be easily obtained.

$$CVaR_\alpha = E(-r| - r \geq VaR_\alpha) \tag{14}$$

C. MEDIUM TERM OPTIMAL OPERATION MODEL OF CASCADE HYDROPOWER STATIONS

1) OBJECTIVE FUNCTION

The goal of cascade hydropower stations to participate in the electricity trading is to maximize profits. During the monthly operation, they can decide whether to participate in day-ahead market to gain profits beyond the medium and long-term contracts according to the actual situation, considering that the cost of hydropower is mainly construction cost and does not affect the optimization of the model, the mathematical expression of the objective function is:

$$\max r = \sum_{i=1}^{N} (r_{1,i} + r_{2,i} + r_{3,i}) \tag{15}$$

where, r is the total power generation revenue of all stations (10^9 CYN); N is the total number of plants.

According to formula (7) ∼ (**12**), the generation revenue of stations mainly depends on the generation capacity e which the calculation formula is **:**

$$e_i = \sum_{t=1}^{T} \eta_i \times Q_{i,t} \times H_{i,t} \times \Delta t \tag{16}$$

$$H_{i,t} = \frac{Z_{i,t-1} + Z_{i,t}}{2} - Z_{i,t}^d - H_{i,t}^d \tag{17}$$

where, t, T are the number of scheduling time periods and the total number of time periods respectively; e_i is the total generating volume of the station i in T period; η_i is the efficiency coefficient of station i; $Q_{i,t}$ is the average power discharge of the station i in period T (m^3/s); $H_{i,t}$ is the water head of the station i in period T; Δt is the Time step; $Z_{i,t}$ and $Z_{i,t}^d$ are the operation water level and downstream tail water level of the station i in period T respectively; $H_{i,t}^d$ is the head loss of the station i in period T.

2) OPERATIONAL CONSTRAINTS

1.hydraulic relation of upstream and downstream reservoirs

$$I_{i,t} = Q_{i-1,t} + S_{i-1,t} + I_{i,t}^s \tag{18}$$

$I_{i,t}$ is the inflow of the station i at period $t(m^3/s)$; $Q_{i-1,t}$ is the generating discharge of the station *i-1* at period t (m^3/s); $S_{i-1,t}$ is the spillages of the station *i-1* at period t (m^3/s); $I_{i,t}^s$ is the local inflow between station *i-1* and station i at period t (m^3/s); It needs to be noted that the behavior of active spillages in order to improve the revenue of stations is generally not allowed by the dispatching agency, so in this paper $S_{i-1,t}=0$.

2. water balance constraint

$$V_{i,t} = V_{i,t-1} + 3600 \times (I_{i,t} - Q_{i,t}) \times \Delta t \tag{19}$$

$V_{i,t}$ is the storage capacity of the station i at the end of period $t(m^3)$.

3. reservoir's water levels constraint

$$Z_{i,\min} \leq Z_{i,t} \leq Z_{i,\max} \tag{20}$$

$Z_{i,t}$ is the water level in front of dam of the station i at the end of period $t(m)$. $Z_{i,min}$, $Z_{i,max}$ are the lowest and highest Z of reservoir i respectively.

4. water level at the beginning and end stage constraint

$$Z_{i,0} = Z_{i,begin} \tag{21}$$

$$Z_{i,T} = Z_{i,end} \tag{22}$$

$Z_{i,begin}$ is the water level of the station i at the beginning of the month (m). $Z_{i,end}$ is the water level of station i at the end of the month (m).

5. generating discharge constraint

$$Q_{i,\min} \leq Q_{i,t} \leq Q_{i,\max} \tag{23}$$

$Q_{i,min}$, $Q_{i,max}$ are the minimum and maximum generation discharge of station i respectively (m^3/s).

6. output constraint

$$P_{i,\min} \leq \eta_i \times Q_{i,t} \times H_{i,t} \leq P_{i,\max} \tag{24}$$

$p_{i,min}$, $p_{i,max}$ are the minimum and maximum output of station i respectively (MW).

7. water level - storage capacity relation constraint

$$V_{i,t} = f_{i,zv}(Z_{i,t}) \tag{25}$$

$f_{i,zv}(\bullet)$ is the relationship function of water level and storage capacity of station *i*.

8. tail water level- discharge relation constraint

$$zd_{i,t} = f_{i,zq}(Q_{i,t}) \tag{26}$$

$f_{i,zq}(\bullet)$ is the relationship function of tail water level and discharge of station *i*.

9. day-ahead trading volume constraint

$$\eta_i \times Q_{i,t} \times H_{i,t} \times \Delta t \geq e_{2,i,t} \tag{27}$$

The above formula indicates that the day-ahead trading volume of the station i in the period t must be less than the generation volume of that day.

IV. RESULTS

With the provincial electricity market dominated by hydropower in China as the background, five hydropower plants A, B, C, D, and E involved in the calculation form a cascade hydroelectric stations from top to bottom, table 5 in appendix provides information of each hydropower plant, including reservoir name, water storage, generation capacity, and operation parameters. 1 is the first stage of cascade hydroplants, and the output process directly affects the operation of the downstream stations. The medium-term scheduling period is one month (30d), and the time scale is one day.

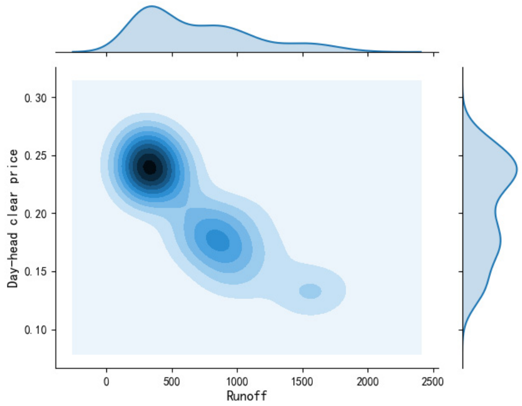


FIGURE 3. The joint distribution and KDE of runoff and DMCP.

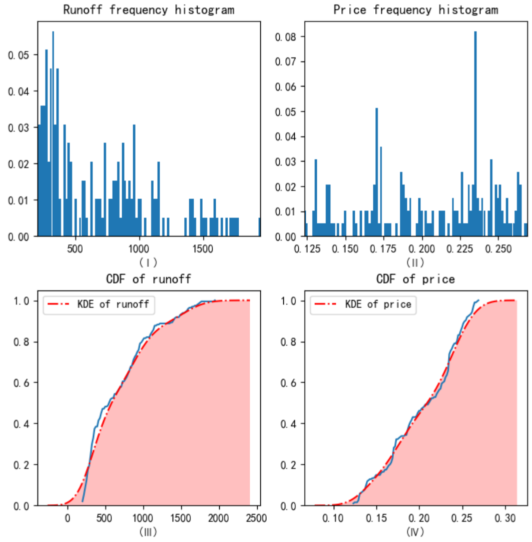


FIGURE 4. KDE diagram of cumulative distribution of runoff and DMCP.

A. CORRELATION ANALYSIS OF DAILY RUNOFF AND CLEARING PRICE OF DAY-AHEAD MARKET

During the wet season (June to October), in order to avoid spillages, the lowest price (0.13 CYN / kWh) is used to increase the generation volume of hydropower stations. Therefore, analyzing the correlation between the daily runoff and DMCP, we need to eliminate the wet season data. The Pearson correlation coefficient of price and runoff is −0.863, so it can be considered that there is a strong negative correlation between daily runoff and DMCP in the other periods, and the joint scatter diagram and univariate KDE diagram of the runoff and price are drawn, as shown in figure 3. The marginal distribution function of the runoff and price are calculated through the KDE method, as shown in Figure 4. I and III are frequency histograms of daily runoff and the DMCP separately, and B and D are cumulative distribution and cumulative distribution of KDE of daily runoff and DMCP separately. It can be seen from II and IV that KDE can well describe the distribution of daily runoff and daily price.

TABLE 2. Parameter estimation and test comparison of different copula functions.

Copula Function	Parameter	Parameter estimate	K-S test value
Gumbel-Copula	θ	1.06	0.0681
Clayton-Copula	θ	0.12	0.0438
Frank-Copula	θ	0.5108	0.0518

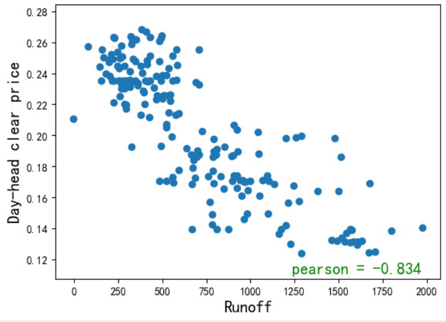


FIGURE 5. scenarios of daily runoff and clearing price in day-ahead market.

Using two-stage MLE method to calculate the fitting parameters and evaluation indexes of three types of Copula Functions to the model in this paper, and the results are shown in Table 2. It can be seen from table 1 that the result of K-S test method corresponding to Clayton copula function in three types of function is the smallest, so Clayton copula function is selected to fit the joint distribution of daily runoff and daily price. When calculating the CVaR of the portfolio income of all stations, we should first evaluate whether the copula function can describe the joint distribution of the daily runoff and DMCP. Using the Copula Monte Carlo method proposed in Section 2 to simulate the scenario which combination of runoff and DMCP, as shown in Figure 5. The Pearson correlation coefficient of the simulation data is −0.843, so it can be considered that the Clayton copula function can better describe the distribution characteristics and correlation between the actual daily runoff and the DMCP. Therefore, the copula Monte Carlo method is used to simulate and generate 100 sets of scenarios in the other seasons, with a period of 30 days. Figure 6 shows two scenarios at random.

B. ANALYSIS OF RISK MEASUREMENT RESULTS

1) ANALYSIS OF THE RESULTS OF MEDIUM-TERM SCHEDULING

Analyze the scenarios of not participating in and participating in day-ahead market, and respectively calculate the operation process of stations in different monthly trading results in dry season before wet season, the operation water level and output process are shown in Figure 7.

In figure I, there are slight differences between the results of the same monthly price and the results of different monthly price. The monthly price of A is the highest, so the output

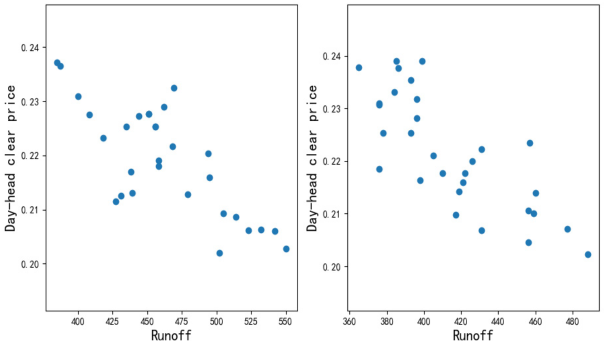


FIGURE 6. Simulation composite scenario.

TABLE 3. CVaR value of trading returns under different market portfolios.

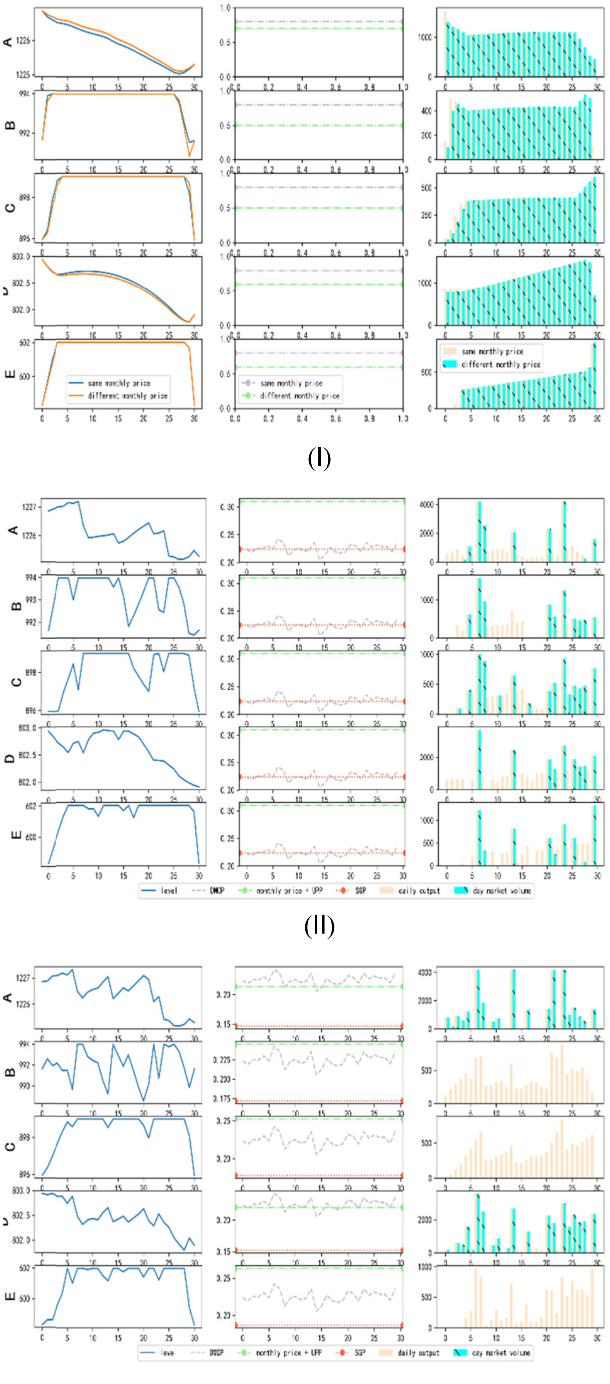
plants	month volume (10^{10}kWh)	month price (CNY/kWh)	UPP (CNY/kWh)	SGP (CNY/kWh)	single market CVaR (10^{10} CNY)	portfolio CVaR (10^{10} CNY)
A	3.25465	0.21358	-0.03	0.17086		
B	0.219463	0.2553	-0.03	0.20424		
C	1.17343	0.2525	-0.03	0.202	6.1843	7.0381
D	3.51301	0.22035	-0.03	0.17628		
E	1.16685	0.2634	-0.03	0.21072		

TABLE 4. Comparison among three scenarios.

scenario	confidence level	CVaR（billon CNY）
1	5	4.301
	95	6.6784
2	5	5.156
	95	5.64
3	5	4.885
	95	7.0381

is increased, and the output of other power stations is little reduced, the monthly total output of all plants is less than the monthly electricity price is same. According to the operating water level process of the each station, in order to increase power generation, A reduces the outflow at the beginning of the month so as to raise the water head, and the inflow of downstream plants also decreases accordingly, resulting in the output of the entire cascade at the beginning of the month being less than the output at the same price.

In figure II, the monthly electricity price + UPP of each plant is larger than that of the DMCP and intersects with the SGP, and the monthly trading volume is less than the practical generating volume. When the stations arrange the day-ahead market output plan, they do not need to wait for the monthly contract to be performed, but arrange the output plan according to the DMCP. On the premise of ensuring the performance of monthly contract within the whole dispatching cycle, we should arrange more volume in the period when the DMCP is high as far as possible. According to the operation water level process, due to the time that involved in day-ahead market is large and dispersed, the fluctuation range of the operating water level of each plant is quite severe,



(I)

(II)

(III)

FIGURE 7. Display diagram of calculation results.

TABLE 5. Main characteristic parameters of cascade hydropower stations.

plants	Regulating performance	Normal level/m	Dead level/m	Minimum discharge /(m3/s)	output coefficient	Start level/m	End level/m	Firm power /MW	Minimum output kW	Maximum discharge /(m3/s)
A	long-term	1240	1903/3/11	0	9.4	1226.86	1225.31	1911/7/1	0	2340
B	season	994	1902/9/14	0	8.5	991.65	991.65	1904/7/27	0	7000
C	daily	899	1902/5/31	0	8.5	895.96	895.96	1903/9/11	0	3000
D	long-term	812	1902/2/3	0	8.81	802.94	801.96	1916/1/6	0	3240
E	daily	602	1901/8/13	0	9.15	598.31	598.31	1904/10/15	0	3327

TABLE 6. Daily market clearing price and daily runoff historical data.

date	runoff(m3/s)	DMPC(CNY/kWh)	date	runoff(m3/s)	DMCP(CNY/kWh)
2016/4/1	461	0.22338	2016/4/16	560	0.21853
2016/4/2	571	0.21288	2016/4/17	663	0.2125
2016/4/3	373	0.20851	2016/4/18	695	0.21649
2016/4/4	425	0.22405	2016/4/19	626	0.2219
2016/4/5	468	0.21436	2016/4/20	886	0.2143
2016/4/6	417	0.21993	2016/4/21	734	0.20673
2016/4/7	639	0.21839	2016/4/22	1003	0.22552
2016/4/8	570	0.2156	2016/4/23	1103	0.22197
2016/4/9	555	0.21436	2016/4/24	1099	0.2098
2016/4/10	842	0.22492	2016/4/25	1409	0.20551
2016/4/11	912	0.22717	2016/4/26	1160	0.19987
2016/4/12	538	0.22001	2016/4/27	1186	0.19377
2016/4/13	695	0.21286	2016/4/28	738	0.20064
2016/4/14	982	0.20737	2016/4/29	766	0.21467
2016/4/15	740	0.22405	2016/4/30	799	0.20746

among which the A and B are the most obvious. The B, C, and E can always maintain high head power generation due to the large upstream outflow.

In figure III, the monthly electricity price + UPP of each plant intersects with the DMCP, and the monthly trading volume is greater than the practical generating volume. When the DMCP is greater than the sum of the monthly price and the UPP, they shall arrange the output plan according to the daily price and participate in the day-ahead market in full volume, so as to gain more benefits to offset the losses caused by unfinished penalty. In particular, B, C and E, the monthly electricity price + UPP over the DMCP, so they do not participate in day-ahead market at all. Based on the process of operation water level of plant, when the plant is not involved in day-ahead market, the water level is relatively stable and the operation level of the plant is kept as high as possible. When involved in day-ahead market, the output of the plant is directly proportional to the DMCP and the water level fluctuates greatly before and after the participating period. Because the output of upstream A fluctuates violently on 15th, the operating water level of B fluctuates accordingly although it does not participate in the day-ahead market.

Based on the above analysis, the optimization model with the operation water level of each plant and daily trading volume as decision variables can dynamically adjust the operation strategy, respond to the daily electricity price signal and hedge the deviation risk caused by runoff fluctuation according to the monthly trading results and the actual operation situation, so as to obtain the maximum generation profit.

2) ANALYSIS ON THE RISK MEASUREMENT OF PORTFOLIO INCOME OF CASCADE HYDROPOWER STATIONS

In order to increase the speed of solution, the multi-core parallel operation method [30]–[34] is used to solve the generation revenue of cascade hydropower stations in all scenarios. The CVaR value of the corresponding portfolio revenue under the given credit level is obtained. Similarly, the corresponding CVaR values in the case of only participating in monthly market are compared. Table 2 lists the calculated results of the above situations.

It can be seen from table 3 that at the given confidence level α =95, the profit of the portfolio increased by 853.8 million yuan, 12.13%, compared with only participating in the monthly market, which proves that participating in the monthly market and the day-ahead market can indeed reduce the operation risk of cascade hydropower stations and increase the generation income.

3) COMPARATIVE ANALYSIS OF CALCULATION RESULTS IN DIFFERENT SCENARIOS

Scenario 1 (runoff uncertainty is considered alone), scenario 2 (DMCP uncertainty is considered alone) and scenario 3 (runoff and DMCP uncertainty is considered separately, the method in this paper) of the example in this paper are respectively calculated and analyzed to analyze the CVaR value of the portfolio return of mid-stage dispatching of cascade hydropower stations. The calculated results are shown in table 3. Scenario 1, scenario 2 and scenario 3 calculate the required historical day-ahead market clearing price as well as the daily runoff data, as shown in appendix B1.

It can be seen from table 4 that under the given confidence level $\alpha = 95$, in scenario 1, scenario 2 and scenario 3, the profits of portfolio trading decreased by 5.11% and 19.86%, respectively. When $\alpha = 5$, the return of trading portfolio in scenario 1 is less than that in scenario 2, with a reduction rate of 16.58%.

It can be seen that considering the uncertainty of runoff and electricity price at the same time can reduce the risk and increase the generation income. The upper limit of portfolio income when considering runoff alone is higher than that when considering electricity price alone, and the lower limit is lower than that when considering electricity price alone, because the fluctuation range of runoff is greater than that of electricity price, the risk of power generation reduction and non performance assessment is far greater than that of electricity price fluctuation, and the calculation results are consistent with the actual situation.

V. CONCLUSIONS

1.The market structure with multiple time scales can effectively restrain the risks brought by the single market, and cascade hydropower stations can choose to participate in different markets according to their actual inflow and electricity prices to hedge the risks brought by other markets, so as to achieve the purpose of increasing returns.

2.Considering the uncertainty of daily runoff and DMCP together, compared with considering both of them alone, can more reasonably evaluate the return risk value, and provide more accurate and objective reference suggestions for cascade hydropower station to arrange output plan and organize participating in various markets.

3.Because the fluctuation range of daily runoff is much larger than that of DMCP, the risk of power generation reduction and failure assessment of cascade hydropower station is much greater than that caused by fluctuation of electricity price, so the fluctuation of runoff needs to be taken into account in actual operation.

APPENDIX

See on Table 5 and 6.

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