Correlation Analysis of Runoff - Electricity Price - Load in Cascade Hydropower Spot Market

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Abstract: Runoff, electricity price, and load are the main random variables in the cascade hydropower spot market. The inter-influence, intertwining and coupling relationship among the three increase the difficulty of power market operation. For this reason, this study first used the system dynamics method to draw the causal circuit diagram of the correlation between power station runoff, discharge price and full network load in the spot market, revealed the correlation mechanism of the three, and analyzed the correlation between the three based on the actual data of the spot market. The results show that there is a significant correlation between the three variables. The price of clearing electricity is positively correlated with the load of the whole network, the correlation coefficient is as high as 0.5238, and the price of clearing electricity is negatively correlated with the reservoir runoff, showing a certain degree of complementarity.

1. Introduction
Since there are complex hydropower connections between cascade hydropower in both time and space dimensions, and the power of each station is in a relationship of mutual influence and mutual restriction, the power spot market with cascade hydropower is more complicated. At present, relevant scholars have conducted special research on the related issues of the electricity spot market with cascade hydropower. For example, Sun Yi [1] et al., based on the analysis of the characteristics of high-proportion hydropower grids, combined with the experience of typical foreign power markets, and proposed a power spot market model for regions with high hydropower proportions. The team of North China Electric Power University Zhang Lizi [2] studied the day-ahead market clearing model of downstream power stations as price receivers, and discussed the impact of time lag on the operation of the power station, targeting the problem of unbalanced matching between the bid-winning power and actual power generation between upstream and downstream power stations with different asset affiliations. In view of the fact that the market power and base power of generator units will coexist for a long time in China, Mo Dong [3] and others put forward a method to decompose the annual base power into the spot market in equal proportion according to the power generation capacity. These studies have achieved important results, but they mainly focus on the construction scheme [4], trading mode [5], spot system design [6], bidding strategy of cascade hydropower [7], medium and long-term electricity decomposition [8], etc. However, there is little research on the relationship of the hydropower electricity spot market runoff - load - clearing price.
Under the power spot market environment, there is a certain degree of uncertainty in clearing electricity prices and load demand, which brings greater challenges to the operation of the power market. Compared with other power markets that use thermal power as the main power source, the cascade hydropower spot market is more controlled by its power supply capacity due to the impact of uncertain runoff. The three main random parameters of runoff, load, and clearing electricity price interact with each other and are intertwined and coupled, making power generation companies' quotation and grid clearing work face huge challenges. Therefore, studying the correlation between runoff, load and clearing electricity price in the spot market and revealing the correlation mechanism of the three is of positive significance for the quotation of power generation companies and the clearing of electricity markets.

2. Mechanism of runoff - electricity price - load correlation
In the mid-1950s, the American scholar Forrester established the system dynamics (SD) theory by combining information theory, cybernetics and system theory. System dynamics uses a combination of qualitative and quantitative analysis methods to study the multi-factor cross and complex information feedback problems of a specific system. It is suitable for dealing with multi-domain, multi-variable, high-order, non-linear, and open system problems, which can reflect the interrelationship between various influencing factors inside and outside the system. And by drawing causal loop diagrams and flow diagrams, the causal relationship between multiple types of variables in a complex system can be expressed in more detail, and the mechanism of correlation between variables can be revealed. The market is a complex nonlinear dynamic system. The electricity market is a market in which electricity is a special commodity as the exchange content. It also has the characteristics of high complexity, non-linearity, and variability. It is a model problem with time as the main variable. There are many kinds of feedback structures in the system, which is in line with the general characteristics of system dynamics.

Power supply and power demand are important components of the power spot market, and power trading is a bridge connecting both supply and demand. Therefore, the system dynamics analysis of the power spot market in this study mainly includes power supply modules, power trading modules and power demand modules. Three basic modules associated with feedback are as in Figure 1. The figure contains two feedback loops. One is the power generation - transaction feedback loop. The power supplier formulates the expected power generation plan for this cycle based on market information and submits it to the trading platform when the market starts. The market operation organization makes unified clearing based on the declaration of both sides of the power generation and consumption and obtains the clearing power and clearing price of each power supplier. The cleared electricity is used as the actual power generation plan of the power supplier in this cycle, which directly guides power generation and affects the amount of water or coal stored. After deducting the cost of power generation, the supplier obtains the profit of this bidding. The actual profit of the supplier determines the success or failure of this bidding, and the supplier adjusts the bidding strategy for the next cycle accordingly. The second is the transaction - electricity feedback loop. Electricity users submit electricity demand curves to the trading platform. Market operating agencies will clear out based on the declarations made by both power generation and consumption to obtain the cleared electricity price. The cleared electricity price is superimposed with the transmission and distribution price to get to the household electricity price. The electricity supplier generates electricity to the grid according to the clearing situation and transmits the electricity to the household through the grid. The clearing situation determines the user's electricity purchase cost. The electricity purchase cost can directly guide the user's electricity consumption in the next cycle. Higher cost can guide users to save electricity, otherwise it can stimulate consumption.
As far as coal power is concerned, humans can control the power generation capacity by controlling the amount of coal stored. The fuel for cascade hydropower generation is river runoff. The runoff is affected by environmental and meteorological factors with great uncertainty. In addition, most hydropower stations do not have the regulation capacity, so the power generation capacity of cascade hydropower is more difficult to control than that of thermal power. For a specific bidding cycle in the spot market environment, the declarable power generation (generation capacity) of cascade hydropower is a complex variable affected by multiple factors. Taking power generation as state variable and power output as rate variable, the flow chart of power supply module of cascade hydropower spot market is constructed, as shown in Figure 2. According to the output calculation formula, the power generation output of a hydropower station is directly affected by the power generation flow and power generation head. The power generation flow is closely related to the storage capacity of the reservoir, the inflow, the total reservoir capacity and other storage parameters, and the power generation flow is a kind of discharge flow. As a form of discharge flow, the power generation flow affects the tail water level of the reservoir, thus affecting the water level drop, namely the power generation head. The power output is not only related to the aforementioned hydraulic factors, but also constrained by the installed capacity of the power station and is also affected by the maintenance plan and the blockage of the unit. In order to ensure the safe operation of the power system, generator sets should be regularly scheduled to carry out preventive maintenance, so that the equipment can always maintain a good technical condition, so
as to reduce failures and prolong life. When the generator set is stopped for maintenance, the number of
generator sets available in the hydropower station will be reduced, which will naturally affect the power
generation capacity of the power station. Water head blocking often occurs in hydropower stations, and
there is a certain blocking capacity in the installed capacity, that is, the capacity that cannot generate
electricity due to too small water head. When the water level of the reservoir is too low or the
downstream water level is too high, and the water head of the hydropower station is less than the design
head of the turbine, even if the guide vanes of the turbine are all opened, the rated power will be
insufficient and the turbine will be blocked. Therefore, the declarable power generation capacity of a
hydropower station in the spot market is affected by the reservoir storage parameters, unit maintenance
plan and blocked situation.

Figure 3 Power demand module flow chart of cascade hydropower spot market

For the demand side, taking the power demand as the rate variable and the total power demand as
the state variable, the flow chart of the power demand module of cascade hydropower spot market is
constructed, as shown in Figure 3. The spot market power demand comes from power users inside and
outside of the province, and the power demand is often affected by local weather and calendar holidays.
The weather factors mainly include temperature, humidity, precipitation, wind speed, sunshine duration,
etc. These factors usually affect the use of lighting and heating (cold) systems, thereby affecting the
power demand of users. The absence of holidays and the length of holidays will not only affect the
production plans of industrial enterprises, but also affect people's mass transfer activities, which will
cause differences in electricity demand between regions. For example, on ordinary weekends, the
electricity consumption of commercial buildings will be greatly reduced, but that of residential buildings
will be moderately increased. Long holidays, such as National Day holiday, will bring a large number
of population migration activities between regions, which will significantly increase the power
consumption of hotels in scenic spots. In addition, as a special commodity, electricity demand has a
certain price elasticity. In general, the market entities on the demand side mainly include large users and
electricity sales companies. Because large users directly participate in the power market, they have direct
decision-making power on power demand. For the purpose of maximizing corporate profits, large users
generally reduce electricity consumption when electricity prices are high and increase electricity
consumption when electricity prices are low, which shows a certain demand elasticity. The electricity
selling companies directly disclose the spot market price to the customers they represent, and guide them
to respond to the price, so as to achieve the purpose of "shifting peak to fill valley and reducing peak
load". Therefore, the total load of the power selling company also shows a certain price elasticity.

The electricity trading module forms the market clearing price, and the clearing electricity price is
the connection point between the power supply side and the demand side. Taking the clearing price as
the state variable and the price change as the rate variable, the power trading module flow chart of
cascade hydropower spot market is drawn, as shown in Figure 4. In the power spot market, market
operating agencies conduct electricity market clearing based on the declarations on the power supply
side and the demand side to form a market clearing price. The market clearing electricity price is largely determined by the relationship between power supply and demand, and price changes can also reflect changes in the relationship between supply and demand. In addition to the real-time balance of power, the particularity of the power market is that the supply of power commodities is not only affected by the power generation capacity of the power station, but also by the power transmission capacity of the grid. Due to the limitation of connecting elements, part of the surplus power cannot be transmitted to the system, so it is easy to form the phenomenon of power grid dimple. In addition, when there is a conflict between the transmission plan and the capacity of the transmission network, line congestion is prone to occur. Lines with larger transmission capacity are less likely to be blocked. Lines with relatively small transmission capacity are more likely to be blocked. When the line is blocked, the grid can only abandon the current low-priced electricity and use other relatively high-priced electricity instead to meet the load demand. Therefore, line congestion tends to raise the market clearing price. In addition, the speed of electricity price change is also affected by the existing electricity price base and market adjustment time. Market adjustment time is the average market clearing time. For example, the day ahead spot market of a province is cleared at a time interval of 15 minutes, so the market adjustment time is 15 minutes.

Figure 4 Flow chart of electricity trading module in spot market of cascade hydropower

In summary, for the spot market with cascade hydropower as the main power source, runoff is the main raw material on the supply side. Clearing price is affected by the relationship between market supply and demand, and both the supply and demand sides will respond to clearing price. Clearing price in turn has a guiding role for power production and consumption. Therefore, in the cascade hydropower spot market environment, there is a non-linear, dynamic and highly coupled relationship between runoff, market clearing prices, and loads.

3. Correlation analysis of runoff - electricity price - load in the spot market

Selecting a hydropower province's recent spot market trial period of a week of clearance electricity prices, the entire network load and a power station storage runoff as the basic data between the three correlation analysis, the sequence range is between October 10 and October 16, 2020, and the time granularity is 5min. The hydropower station is selected as the downstream control reservoir of a certain river basin, which has the ability of seasonal regulation and good representativeness.

The clearing price, the load of the whole network and the inflow runoff data of a power station are plotted, as shown in Figure 5. During this period, the average clearing price is 100.61 yuan / MWh, the average runoff is 1951.48 m3 / s, and the average load is 24.8468 million KW. October 10 and October 13 are selected as typical representatives of holidays (Saturday) and working days (Tuesday), and the curves are drawn as shown in Figure 6 and figure 7. It is found that the average load on working days is 380000 kW higher than that on holidays. Affected by the low demand, the average clearing price on holidays is 9.24 yuan / MWh lower than that on working days. Clearing price, whole network load and runoff show a strong correlation, in which the load and clearing price show a strong synchronization, and the change trend is basically the same, showing the characteristics of "peak to peak, valley to Valley" on the curve, while clearing price and inflow runoff are opposite. When the runoff is high, clearing price is low, but when the inflow is large, clearing price is high.
In order to quantify the two-phase relationship between the three variables, the Pearson correlation coefficient method is used for statistical analysis, and the calculation formula is shown in formula (1):

\[
\rho_{X,Y} = \frac{\sum (X - \bar{X})(Y - \bar{Y})}{\sqrt{\sum (X - \bar{X})^2 \sum (Y - \bar{Y})^2}}
\]  (1)
Where: \( X \) and \( Y \) are two variables, \( \bar{X} \) and \( \bar{Y} \) represent the average value of variable \( X \) and \( Y \) respectively, and \( \rho_{X,Y} \) represent the Pearson correlation coefficient of \( X \) and \( Y \).

The Pearson correlation coefficient among clearing price, whole network load and inflow runoff data of a power station is calculated in table 1. It is found that there is significant correlation between the three variables, among which clearing price and whole network load have medium positive correlation, and the correlation coefficient is as high as 0.5238; the price of clearing electricity is negatively correlated with the inflow runoff, showing a certain degree of complementarity.

|                  | Total network load | Clearing price | Inflow runoff |
|------------------|--------------------|----------------|--------------|
| Total network load | 1                  | 0.5238         | 0.1357       |
| Clearing price    | 0.5238             | 1              | -0.1885      |
| Inflow runoff     | 0.1357             | -0.1885        | 1            |

4. Conclusion
This research firstly used system dynamics method to draw the causal loop diagram of the relationship between the power plant runoff, clearing price and the whole network load under the spot market, and revealed the correlation mechanism of the three. It found that the clearing price as an intermediate variable connected the runoff and load, which made the three have a close relationship of nonlinear, dynamic development and high coupling. Secondly, based on the actual data of a cascade hydropower spot market, the correlation between the three was analyzed. The results showed that the three variables had significant correlations. Among them, the clearing electricity price and the whole network load were moderately positively correlated, with the correlation coefficient as high as 0.5238; the clearing electricity price was negatively correlated with the inflow runoff, showing a certain degree of complementarity.

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