A Method of Operating State Estimation of Pumped Storage Power Station Based on Load Peak-Valley-Normal Prediction

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Abstract. In order to make the power system absorb more renewable energy and improve the flexibility of power grid operation, one of the effective methods is to configure pumped storage power station in power system. In order to reduce the frequent start-up and shutdown of pumped storage power station, “A Method of Operating State Estimation of Pumped Storage Power Station Based on Load Peak-Valley-Normal Prediction” is proposed in this paper. This method is based on FCM clustering algorithm classifies peak-valley-normal loads at one time of power grid, evaluates the operation state of pumped storage power station on this basis, and finally applies it to the operation cost optimization model of wind-solar-fire-storage system to evaluate the renewable energy absorption capacity and economic operation cost. The simulation results prove that this method can reduce the start-up and shutdown times of pumped storage power station and is of positive significance for maintaining long-term and stable operation of pumped storage power station.

1. Introduction

With the increasing proportion of renewable energy in power supply of power grid, more and more attention has been paid to its abandonment. In most areas of China, thermal power units are still used as the main regulating power source. However, thermal power units have the problems of low climbing speed and high minimum technical output, which will result in waste of renewable energy under the constraint of "ready-to-use" of power grid system. In addition, the load "peak-valley difference" of China's power grid system is increasing day by day, and the anti-peak regulation characteristics of renewable energy have aggravated the contradiction between supply and demand of power grid. In view of this, load transfer is a new idea to solve the contradiction between supply and demand of renewable energy and power grid.
In order to make better use of renewable energy, pumped storage power plant is one of the effective ways to improve the flexibility of power grid. With the wide application of variable-speed pumped storage power station and the development of power electronics technology, the pumped storage power of pumped storage power station is continuously adjustable and its application field is more extensive [1].

At present, the application of pumped storage power station in power grid system dispatching mainly considers its fast response performance and bi-directional regulation capability considering both generation and storage. The impact of its fast response characteristics on the power grid is mainly reflected in its improvement of network flexibility. Pumped storage power plant is characterized by fast start-up and fast power regulation, which can provide guarantee and support for grid connection of renewable energy sources. When the volatility of renewable energy is too high to output continuous and stable power, pumped storage power plants can respond quickly to improve the ability of power grid system to cope with the fluctuation of renewable energy power. Therefore, it will not greatly affect the power balance of power grid, thus reducing the impact of uncertainties of renewable energy grid connection on power grid and thus alleviating the adjustment pressure of power grid [1-3]. The influence of its bidirectional regulation capability, which takes into account both generation and storage, on power grid is mainly reflected in its peak shaving and valley filling. In the "high-energy stage" of renewable energy, the output of renewable energy may exceed the maximum that can be absorbed by the system. Through the energy storage function of pumped storage power station, excess energy can be stored to reduce the waste of renewable energy, thus achieving the purpose of "valley filling". In the "insufficient stage" of renewable energy, pumped storage power station can release energy and reduce the output of thermal power unit. Force to save operating costs, so as to achieve the purpose of "peak cutting". However, although the pumped storage power plant has high flexibility, frequent start-up and shutdown and changing its operation state may cause potential damage to turbine blades [4]. Therefore, the number of start-up and shutdown times of pumped storage in short time should not be too much.

In conclusion, if the operation state of pumped storage can be predicted in advance, it is of positive significance for safe and stable operation of pumped storage power plant and economic optimization dispatch[5].

In order to solve the above problems, demand forecasting the operation state of pumped storage power station. Previous studies often directly set the maximum number of start-up and shutdown times of pumped storage power plants in optimization algorithm [6-8]. This method may lead to the reduction of utilizing efficiency of pumped storage power plant, and is prone to the phenomenon of "very short-term" pumping - short storage time and generation time, which will be unfavorable to the normal dispatching and operation of pumped storage power plant. Based on the above research basis and current situation, this paper presents “A Method of Operating State Estimation of Pumped Storage Power Station Based on Load Peak-Valley-Normal Prediction”, which classifies load peak-valley-normal forecast by FCM clustering algorithm. The main principle of this method is to classify the load subordination function at a certain time of the day based on a large amount of data, to determine the probability of load belonging to three types of peak-valley-normal and to estimate the operation state of pumped storage power station on this basis. This method can reduce the blindness of start-up and stop control of pumped storage power station.

In this paper, a typical scenario with renewable energy in a region of China is taken as the research object, and the operation state of pumped storage units is estimated by using the method of operating state estimation based on load peak-valley-normal prediction. The estimated operation state of pumped storage units is applied to the optimization calculation of economic operation of power grid, and the difference of operation results of pumped storage units dispatched by conventional means is compared to confirm the validity of this method. After simulation verification, this method can improve the capacity of renewable energy dissipation of power system and simultaneously has operational economy, which has certain practical value.
2. Mathematical Model

2.1. Classification Method of Peak-Valley-Normal of Load

This paper intends to classify which type of load (Peak-Valley-Normal) belongs to a certain period of time by FCM clustering. Because FCM clustering algorithm is different from traditional hard clustering analysis in hard partition characteristics, by introducing the concept of membership function, the relationship between objects and clusters is extended to be described by arbitrary values on [0,1] closed interval. Thus, by judging the value of membership function, the object can be divided into which cluster [9,10,11], which is more in line with the characteristics of load division at a certain time.

Let the domain be \( X \), called Mapping \( \mu_x : X \rightarrow [0,1] \)

\[
\mu_x : X \rightarrow [0,1] \quad \mu_x(x) \in [0,1] \quad (1)
\]

For any \( x \in X \), a number \( \mu_x(x) \in [0,1] \) can be determined to describe the degree to which \( X \) belongs to \( A \). It is defined as a subordination function of \( \mu_x(x) \). The subordination degree of elements in \( X \) to a fuzzy subset \( A \) is described by a constant \( \mu_x(x) \). The closer the \( \mu_x(x) \) membership is to 0, the smaller the degree to which \( X \) belongs to \( A \); the closer the \( \mu_x(x) \) is to 1, the greater the degree to which \( X \) belongs to \( A \).

Set load data set \( P_X = \{ P_{x1}, P_{x2}, P_{x3} \} \), and divide data set \( X \) into three categories by FCM clustering, in which the set of clustering centers can be represented as \( V = \{ v_1, v_2, v_3 \} \). In the fuzzy partition, each data object is described as belonging to a certain class with certain subordination value, but not strictly classified into a certain class.

The second data sample \( P_{x1} \) in the data set \( P_X \), the subordination \( \mu_y \) of class \( j \), is represented by the following numerical relationships:

\[
\sum_{j=1}^{3} \mu_j = 1, \quad 0 < \mu_j < 1 \quad (2)
\]

By comparing the subordination degree, the load can be divided into three types, Peak-Valley-Normal load. And the proportion of classification can be controlled by adjusting the index size of subordination degree.

2.2. Estimation of Pumped Storage Operation

The load can be divided into three types of peak-valley-normal by section 2.1. When the load is peak-valley-normal, the pumped storage power station should be more inclined to operate in power generation mode in order to reduce the peak load; when the load is cereal load, the pumped storage power station should be more inclined to operate in storage mode in order to fill the valley load; when the load is in normal load state. Pumped storage should be more likely to be out of service.

The above analysis shows that:

\[
\begin{align*}
U'_{\text{Pump},k} &= \begin{cases} 1 & P_{(l,k)} \in A_{\text{valley}} \\ 0 & P_{(l,k)} \notin A_{\text{valley}} \end{cases} \\
U'_{\text{Tur},k} &= \begin{cases} 1 & P_{(l,k)} \in A_{\text{Peak}} \\ 0 & P_{(l,k)} \notin A_{\text{Peak}} \end{cases}
\end{align*} \quad (3)
\]

Among them, \( U'_{\text{Pump},k} \) and \( U'_{\text{Tur},k} \) are estimated states at k time of pumped storage power station.

They estimate storage and power generation estimated states 1 are in this state 0 are not in this state; \( P_{(l,k)} \) is the load value at k time of power grid; \( A_{\text{Peak}} \) and \( A_{\text{valley}} \) indicate peak load and cereal load after load classification at a certain time.
Pumped storage power station has two operating modes, storage mode and power generation mode. Essentially, the conversion of electric energy to gravity potential energy is related to motor power. The gravity potential energy and energy conversion model is shown in equation (5) - (6):

\[ P_{\text{pump},k} = -\eta_{\text{pump}} \rho g Q_{\text{pump},k} h \]  
\[ P_{\text{tur},k} = -\eta_{\text{tur}} \rho g Q_{\text{tur},k} h \]

\( \eta_{\text{pump}} \) is storage efficiency; \( P_{\text{pump},k} \) is storage power at \( k \); \( \eta_{\text{tur}} \) is generator efficiency; \( P_{\text{tur},k} \) is generator power; \( \rho \) is water density, 1000kg/m\(^3\); \( g \) is gravity acceleration; \( h \) is head height of reservoir; \( Q_{\text{pump},k} \), \( Q_{\text{tur},k} \) are pumped and discharged water volume at \( k \) period of pumped storage power station.

At the same time, since the pumped storage power plant can not operate in both the generation mode and the storage mode, but can be in standby state at the same time, the working state can be expressed by mathematical relationship equation (7).

\[ U_{\text{tur},k} + U_{\text{pump},k} \leq 1 \]  

\( U_{\text{tur},k} \) and \( U_{\text{pump},k} \) respectively indicate whether the pumped storage power station is in the state variable of generation mode and storage mode, and 1 is in this state 0 is not in this state.

2.3. Optimization model of operation cost for Thermal-Wind-PV-Storage combine system

The estimated operating state of pumped storage unit is applied to the optimization of operating cost of wind-solar-fire-storage system. In order to reduce the phenomenon of "discarding the wind and discarding the light", the penalty cost of "discarding the wind and discarding the light" electric quantity and the sum of operating and retrofitting costs of all units are taken as the optimization objectives, and the optimization objective function is:

\[ \min F = C_{th} \sum_{k=1}^{T} P_{th}(k) + C_{re} \sum_{k=1}^{T} \left( P_{\text{max},\text{wind}}(k) + P_{\text{max},\text{PV}}(k) - (P_{\text{wind},k} + P_{\text{PV},k}) \right) + C_{s} \sum_{k=1}^{T} (K_{\text{pump}} + K_{\text{tur}}) \]  

Among them, \( T \) is the total number of simulation periods, \( C_{th}, C_{re} \) and \( C_{s} \) are the cost coefficients of thermal power units, the abandonment cost coefficients of each new energy unit (in this paper, wind power and photovoltaic abandonment costs are the same), and the start-up and shutdown costs of pumped storage power station; \( P_{th}(k) \) is the output of thermal plant; \( P_{\text{max},\text{wind}}(k), P_{\text{max},\text{PV}}(k) \) and \( P_{\text{wind}(k)}, P_{\text{PV}(k)} \) of thermal power units at \( k \) time, which are wind power respectively, and the maximum output of photovoltaic theory and actual value. \( K_{\text{pump}}, K_{\text{tur}} \) are the daily starting and stopping times between the pump and the generator.

The constraints considered by the optimization model include:

Equation constraints are established for the objective function of the optimal economic benefit operation model.

1) In order to maintain the balance of electric quantity in power system, equation constraints need to be established, Equation (9)

\[ P_{\text{tur},k} - P_{\text{pump},k} + P_{\text{wind},k} + P_{\text{PV},k} + P_{\text{el},k} = P_{L,k} \]  

At the same time, it is necessary to define the operating boundary of each unit and establish inequality constraints.

2) Generation power range constraints: the generation capacity of each type of unit meets their respective maximum and minimum generation capacity constraints.
\[
0 \leq P_{\text{wind}(k)} \leq P_{\text{wind}(k)}^{\text{max}} \\
0 \leq P_{PV(k)} \leq P_{PV(k)}^{max} \\
0 \leq P_{\text{th}(k)}^{\text{min}} \leq P_{\text{th}(k)} \leq P_{\text{th}(k)}^{\text{max}} \\
0 \leq P_{\text{Tur}(k)} \leq U_{\text{Tur}(k)} U_{\text{Tur}(k)}^{\text{max}} P_{\text{Tur}(k)}^{\text{max}} \\
0 \leq P_{\text{Pump}(k)} \leq U_{\text{Pump}(k)} U_{\text{Pump}(k)}^{\text{max}} P_{\text{Pump}(k)}^{\text{max}}
\] (10)

\( P_{\text{Tur}(k)}^{\text{max}} \) and \( P_{\text{Pump}(k)}^{\text{max}} \) are respectively the theoretical maximum outputs of pumped storage power station when the k time, \( P_{\text{th}(k)}^{\text{max}} \) and \( P_{\text{th}(k)}^{\text{min}} \) are in the generation mode and storage mode. The maximum and minimum output of thermal power unit in k-period respectively.

3) Climbing restriction of thermal power unit:
\[
-R P_{\text{a}(i,k)}^{\text{max}} \leq P_{\text{a}(i,k)} - P_{\text{a}(i,k-1)} \leq R P_{\text{a}(i,k)}^{\text{max}}
\] (11)

Among them, \( R \) is the climbing speed of thermal power unit.

4) Rotary Standby Constraints:
\[
\begin{align*}
P_{\text{th}(k)}^{\text{max}} - P_{\text{th}(k)} - \left( P_{\text{wind}(k)} + P_{PV(k)} \right) & \geq P_+ \\
P_{\text{th}(k)} - P_{\text{th}(k)}^{\text{min}} - \left( P_{\text{wind}(k)} + P_{PV(k)} \right) & \geq P_-
\end{align*}
\] (12)

\( P_+ \) and \( P_- \) are positive and negative respectively.

5) Start-stop times constraints

Generally, the operation cycle of pumped storage power station is daily. The peak load occurs once or twice during the day, and the excess water from the lower reservoir needs to be sucked into the upper reservoir at midnight so that it can be used the next day. Therefore, the number of start-up and stop should not be too much.
\[
\begin{align*}
K_{\text{Pump}} & \leq M \\
K_{\text{Tur}} & \leq M
\end{align*}
\] (13)

\( M \) is the maximum number of start-up and shutdown of units in pumped storage power plant.

3. Example Analysis

Taking a power grid in Northwest China as an example, this example uses the load peak-valley-normal forecasting method proposed in this paper to estimate the operation state of pumped storage units in this area, and evaluates the operation state of pumped storage units to improve the power grid system by comparing the performance of renewable energy consumption and operation cost in this scenario with the system operation cost optimization model. The area has 150MW installed wind power and 150MW installed photovoltaic power, accounting for about 40% of the total installed wind power in the whole region. This research select the output data of wind power and photovoltaic power from 2018 as samples. The simulation time step is 15min.

The parameters of each experimental unit are shown in Table 1

| Unit type | Maximum output(MW) | Minimum output (MW) | cost(¥/kwh) |
|-----------|--------------------|---------------------|-------------|

Table 1. Parameter of each unit.
3.1. Load and Operation State Forecast

3.1.1. Load forecasting

This section will analyze the application price effect of load peak-valley-normal classification method based on FCM clustering algorithm. The FCM clustering algorithm proposed in Section 2.1 is used to classify the daily loads. Among them, the load classifications at one time during the operation time are peak, cereal and even. The proportion and average size of the three loads are shown in Table 2.

| Table 2. Proportion of cost load forecast. |
|------------------------------------------|
| Load type   | Percentage | Average load (MW) |
| Peak        | 31.25%     | 232.77            |
| Valley      | 21.875%    | 197.68            |
| Normal      | 46.875%    | 221.188           |

It can be seen that category Normal load accounts for the highest proportion, so it should be increased.

At the same time, typical daily classification of load classification subordination is shown in Figure 1.

![Typical daily classification of load classification subordination](image)

The results of typical daily load peak-valley-normal classification are shown in Figure 4. According to the analysis of load classification every day, it can be concluded that 9:30 to 12:45, 18:15 to 22:30 are peak periods of power load and can be classified as peak loads. 24:00 to 5:15 per day can be classified as cereal load; 22:30 to 24:00, 5:15 to 9:30, 12:45 to 18:15 per day is peak period of electric load and can be classified as equal load.

3.1.2. Estimation of operation state of Pumped Storage Power Station

According to the results of Section 3.1 load forecasting, the distribution of various loads can be known. According to Section 2 equation (5) equation (6), the operation state estimation of pumped storage power station can be obtained, and the operation state estimation of typical days can be obtained as shown in Figure 2.
3.2. Comparison of Thermal-Wind-PV-Storage combine system

The estimated operating state of 3.1 pumped storage power plant is applied to the combined wind-solar-fire-storage system for simulation experiment. Comparisons are made between the operation of pumped storage power station and the state operation of the pumped storage power station by combining the optimization model established in Section 2.4 with the wind-light-fire-storage system. The comparison of the wind abandonment rate, light emission rate, total renewable energy abandonment rate and the operation cost of each scenario is shown in Table 3.

| Estimation method | Waste rate of wind power | Waste rate of photovoltaic power | Waste rate of Renewable Energy | Compensation expenses (x10,000 ¥) |
|-------------------|--------------------------|---------------------------------|-------------------------------|----------------------------------|
| No use            | 8.5%                     | 7.2%                            | 6.3%                          | 346.32                           |
| use               | 6.4%                     | 5.1%                            | 5.7%                          | 328.19                           |

Through the above research, it can be found that the simulation results under the operation state estimation of Pumped Storage Power Station show that the rate of renewable energy discarded is lower and the economic operation cost is lower. Considering the economic benefits of the local renewable energy absorption, the operation state of pumped storage power station should be estimated by the method of operation state estimation based on load peak-valley-normal prediction.

4. Conclusion

This paper takes the regional power grid with renewable energy in a region of China as the research object, proposes a method of operating state estimation of pumped storage power station based on load peak-valley-normal prediction and applies it to the operation cost optimization model of wind-solar-fire-storage combined system. Pumped storage power plant operation state estimation is used to estimate the pumping state of the pumped storage power plant and to predict the operation state of the unit. According to the condition of the state estimation, the appropriate optimum operation mode is selected, and the power network performance under different conditions is compared with that without prediction. The results show that the operation state estimation of pumped storage power station can effectively improve the flexibility of power grid and help to improve the consumption capacity of renewable energy in power grid. Meanwhile, the power grid can improve the economy of power grid operation and reduce the number of start-up and shutdown of pumped storage power station. Therefore, this method has certain practical significance.
Acknowledgment
This work is supported by State Grid Ningxia electric power company science and technology project "Research on regulation resource optimization planning technology to enhance system flexibility" (No. b442ny190012).

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