A coordination controller in variable speed pumped storage plant

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Abstract. With the integration of increased variable renewable energy generation, much attention has been devoted on the development of pumped storage. The variable speed pumped storage technology has become a research focus due to its wide operating range, high production efficiency and strong power regulation ability. Moreover, the coordination controller is the key component of variable speed pumped storage plant (VSPSP), it can coordinate the joint operation of governor and converter. The coordinated controller is studied in this work. Aiming at the coordinated control between governor and converter, the novel adaptive strategy of maximum efficiency point tracking is proposed. First, the optimal efficiency curves are described based on model experiment; and then the optimal operating curves of variable speed unit in the operation region is presented based on the BP neural networks; the convergence analysis of mean square error and regression analysis are applied to verify the reliability of results. Aiming at the application of adaptive strategy in the coordination controller, and ensuring the real-time performance, a new effective digital interpolation method is put forward, using programmable logic controller. The signal flows of the control system in variable speed unit are clarified. The proposed adaptive strategy could be easily applied in engineering, providing a technical means for the efficient and flexible operation of VSPSP.

1. Introduction

With the integration of increased variable renewable energy generation [1] and advent of liberalized electricity market [2], much attention has been devoted on the development of pumped storage system, as it has many prominent advantages of ensuring the safe and steady operation of power grid. The 13th five-year plan of energy in China [3] puts forward the goal of strengthening the construction of power-regulating and improving the flexibility of system, with the key means of pumped storage plants. Improving the stability of the power system with high penetration of clean energy is a prerequisite for human to use clean energy on a large scale. The fast and stable regulation of pumped storage plants, is a basic guarantee for supporting scenarios of renewable energy systems. Furthermore, variable speed pumped storage plant (VSPSP) has become an emerging technology in the global pumped storage industry, with the advantages of rapidity, high efficiency, flexibility and reliability [4].
The variable speed operation can improve the dynamic performance of pumped storage units, such as mitigating the cavitation effects, alleviating water hammer disturbances, and optimizing transient processes. In the past decades, quite a number of meaningful investigations have been conducted for VSPSP, mainly including numerical simulation, model experiment, the advantages of variable-speed operation, dynamic characteristics, coordinated operation with renewable energy. For numerical simulation, the numerical simulation platform of VSPSP was built, and the dynamic performances of variable speed and fixed speed units were compared in this platform [5]. The control strategy of variable speed unit (VSU) was optimized based on the simplified converter model [6]. For the model experiment, T. Kuwabara et al. elaborated the design principle and operation procedure of VSU in Ohkawachi pumped storage plant in Japan, and conducted field measurement analysis on the quick response of the active power, demonstrating the advantage of rapidity and flexibility in variable speed operation [7]. D. Borkowski et al. [8] developed a small variable speed hydropower unit based on a permanent magnet generator, and conducted actual commissioning and performance experiments. For the performance and advantage of variable speed operation, the rapidity can be reflected in the quick response of active power regulation, which can suppress the power oscillation and improve the frequency stability of the power system. The flexibility is embodied in the turbine mode, the pumped-turbine can adapt to a wider range of water head to ensure that the unit runs at the optimal operating conditions [9]. The efficiency is illustrated in improving the operating efficiency of pump mode and turbine mode by changing speed, which can increase average power generation by 20% [10]. For the dynamic characteristics of VSPSP, the regulation of frequency and power is realized through the coordinated operation of the converter and the governor, which is conductive to improving the stability of power grid. VSPSP can compensate for generation of variable renewable energy (VRE) and greatly reduce wind curtailment [11]. The advantage of VSPSP for mitigating power variations was been studied in [12], which could be an important source of support for the investment and development of variable-speed pumped storage technology. Good dynamic characteristics of VSPSP provide necessary conditions for its coordination operation with renewable energy.

Although many meaningful works have been carried out for VSPSP. However, there is still a lot of room to be improved and developed, which are also the features of this paper expounding as follows:

1. The coordination controller is the key component of the VSPSP, coordinating the joint operation of the governor and the converter. To the best of the author’s knowledge, a coordination controller of VSPSP has been rarely reported in existing studies. (2) The adaptive strategy of maximum efficiency point tracking is the core of the coordination controller, determining the optimal operation of VSPSP. It should be taken seriously in the variable speed operation.

A coordination controller is developed in this paper. Aiming at the coordinated control between governor and converter, the novel adaptive strategy of maximum efficiency point tracking is proposed. First, the optimal efficiency curves are described based on model experiment and BP neural networks; then, the operation curves of variable speed unit in the operation region is presented. Aiming at the real-time performance of coordination controller, a new effective digital interpolation method is put forward, using programmable logic controller (PLC).

The rest of the paper is organized as follows. In Section 2, the adaptive strategy of maximum efficiency point tracking is proposed. In Section 3, the hardware of coordination controller is introduced, and the digital interpolation method is depicted. The discussion and conclusions are respectively drawn in Section 4 and Section 5.

2. The adaptive strategy of maximum efficiency point tracking

The variable speed operation can increase the turbine operating discharge and give higher efficiency over a wide operating range [13]. It is particularly advantageous under conditions different from the original design conditions. Changing of the hydrological conditions requires adjustments to the operating points of pumped storage unit by coordination controller. Therefore, the adaptive strategy of maximum efficiency point tracking is proposed.

2.1 The source of measured data
The experimental platform of variable speed pumped storage unit as shown in Fig. 1, located in experimental hall of pumped storage plants of the State Key Laboratory of Water Resources and Hydropower Engineering Science of Wuhan University, is the research instance in this paper. The model experiments, including efficiency tests, pressure fluctuation tests and energy characteristic tests, were conducted with the assistance of Harbin Electric Corporation.

Model unit contains the reversible pump turbine, the doubly fed induction machine, thrust bearings and shafting, etc. The model pump turbine includes volute, socket ring, fixed guide vane, head cover, movable guide vane, runner, bottom ring and draft tube, etc. The speed variation range is ±8%, and the rated power is 78.13 kW. The model runner meet the IEC standard with a reference diameter of 284.3 mm, and the number of runner blades is 7. The physical parameters of the experiment platform are shown in Table 1.

![Figure 1. Photo for part of the experiment platform of variable speed pumped storage unit under wave disturbance.](image)

| Parameters                  | Prototype value | Scale | Model value |
|-----------------------------|-----------------|-------|-------------|
| Rated speed                 | 500 rpm         | 0.5   | 1000 rpm    |
| Rated discharge             | 11.45 m³        | 32    | 0.36 m³     |
| Maximum head                | 124.2 m         | 4     | 31.05 m     |
| Minimum head                | 93 m            | 4     | 23.25 m     |
| Diameter                    | 1137.20 mm      | 4     | 284.3 mm    |
| Rated power                 | 10000 kW        | 128   | 78.13 kW    |
| The speed variation range   | ±8%             | /     | ±8%         |
| Rated voltage               | /               | /     | 380 V       |

2.2 Optimal efficiency curves
The optimal efficiency curves are the basis of maximum efficiency point tracking strategy. It should be derived based on efficiency tests rather than inversion with comprehensive characteristic curves.

The discrete measured data of efficiency tests can be depicted as follows:
\[
A_1 = \{N_{11}, Q_{11}, \eta\}, \quad A_2 = \{N_{11}, Q_{11}, y\} \tag{1}
\]
Here, \(N_{11}\) is the unit speed, \(Q_{11}\) is the unit discharge, \(\eta\) is the corresponding efficiency of pump turbine, \(y\) is the guide vane opening.

Two neural networks are constructed to summarize the relationship between these measured data. It can be depicted as follows:
\[
BP_1 : \{N_{11}, Q_{11}\} \rightarrow \eta, \quad BP_2 : \{N_{11}, Q_{11}\} \rightarrow y \tag{2}
\]
Here, \(N_{11}\) and \(Q_{11}\) are input variables, \(\eta\) and \(y\) are output variables.
According to the model experiment results, the high efficiency areas of the comprehensive characteristic curves are divided. The range of \( N_{11} \) is set from 46 to 64; the range of \( Q_{11} \) is set from 250 to 850. The matrix \( B_{200 \times 200} = [N_{11}, Q_{11}] \) can be obtained by \textit{linspace} function of MATLAB.

The matrix \( B \) is fed into the neural network \( BP \), then the corresponding value of \( \eta \) can be predicted. And the data sequence \( A_1 \) and \( A_2 \) can be extended to \( A_i = \{ N_{11}, Q_{11}, \eta, y, p_{11} \} \) based on the Equation (3).

\[
p_{11} = \gamma Q_{11} \eta \tag{3}
\]

Here, \( \gamma \) is bulk density of water.

According to the field condition of the platform, the range of water head is set from 23.25 m to 32.20 m. The data sequence \( A_i = \{ N_{11}, Q_{11}, p_{11}, N, H, P, \eta, y \} \) under each water head can be calculated based on Equation (3), (4) and (5).

\[
P = p_{11} \cdot D^2 \cdot H^{1.5} \cdot \eta, \tag{4}
\]

\[
N = \frac{N_{11} \sqrt{H}}{D} \tag{5}
\]

Therefore, power equivalent contour can be obtained as shown in Fig.2 (blue curves). The optimal efficiency curve can be solved by selecting the highest efficiency point on the power equivalent contour, as shown in Fig.2. As shown in Fig.2, within the variable speed range, the optimal efficiency points can be solved according to the corresponding unit physical parameters. It is worth noting that the maximum efficiency point corresponds to the minimum discharge point on each \( p_{11} \) equivalent curve. Furthermore, the optimal efficiency point tracking can be converted to the \( p_{11}-N_{11} \) coordinate plane as shown in Fig.3. Moreover, the optimal speed at a given active power can be calculated under the premise of maximum efficiency.

\[\text{Figure 2. The comprehensive operating curves of variable speed unit.}\]
2.3 Optimal operating curves based on BP neural network

The coordination controller can realize coordinated operation between governor and converter based on optimal operating curves. It can receive the signals of output power and water head, then calculate the optimal rotational speed and guide vane opening in real time, and transmit to the converter and governor respectively. Therefore, the optimal operating curves should meet the applied requirements of the coordination controller.

However, due to experimental conditions and cost constraints, the sequences of field measurement data, based on the model experiment, are sparse, so it is difficult to fill the interpolation requirement of the coordination controller. The BP neural networks, which can generalize the inherent law of characteristic of the VSU, are applied to overcome the above shortcomings. The BP model consists of double inputs \((P, H)\), double outputs \((N, y)\), and five hidden layers taking account of the coupling relations in the physical parameters of VSU. Here, \(P\) is the output power, \(H\) is the water head, \(N\) is the rotational speed of pump turbine, and \(y\) is the guide vane opening.

The main process is depicted as follows:

Step 1: Define the operation region of the VSU. According to the field condition of the platform, the range of water head is set from 23.25 m to 32.20 m; the rotational speed is set from 920 rpm to 1020 rpm, the range of output power is set from 30 kw to 80 kW, the maximum of guide vane opening is set to 100%.

Step 2: Set the parameters of neural network. The maximum number of iterations is 4000, the number of each hidden layer nodes is 10, the learning rate is 0.005, and the training objective error is \(2e^{-15}\), the training algorithm is 'trainlm'. The number of training data is 6600, and the number of test data is 2800. The structure diagram of BP neural network is shown in Fig.4.

Step 3: Analyze the reliability of training process of neural network. The convergence analysis of mean square error and regression analysis are applied, which can be shown in Fig.5 and Fig.6.

Step 4: According to the divided operation regions of Step 1, each operating point \((P, H)\) in this area can get corresponding rotational speed \(N\) and guide vane opening \(y\) under the premise of optimal
efficiency. The data sequence $A_t$ is enriched and extended. It can be embedded directly into the coordination controller.

As shown in Fig.5, the best validation performance is $2.174 \times 10^{-4}$ at epoch 895. In order to avoid the over-fitting in training process of neural network, the regression analysis of training, cross-validation, testing should be conducted as shown in Fig.6. $R$ is the correlation coefficient. In Fig.6, the output values of training, cross-validation, testing and all sample points are distributed on the regression line. The correlation coefficients are all very close to 1. It indicates that the prediction model of BP neural network can correctly fit the internal relationship of physical parameters of VSU. As shown in Fig.7, the maximum values of prediction error are 0.11 and 0.039. It illustrated that the inherent law of characteristic can be generalized from the existing data sequence thanks to the strong self-learning and predictive ability of the BP neural network. It is necessary to enrich and extend the data sequences that are hard to get from the manufacturer.

![Figure 5. The convergence curve of BP neural network.](image1)

![Figure 6. Regression analysis of BP neural network.](image2)
After the above steps, the relationships of the physical parameters of VSU at the optimal efficiency can be illustrated in Fig.8 and Fig.9. In the operating range of VSU, the corresponding rotational speed and guide vane opening can be found according to the power and water head. It lays a foundation for the operation of the coordination controller.
3. The application of adaptive strategy in the coordination controller

Programmable logic controller (PLC) has been widely used in the automatic control of industrial machinery, has become one of the most important, the most popular, the most widely used industrial control devices. It is the preferred control hardware for the coordination controller. However, there are two key bottlenecks in application. One is logic complexity of BP neural networks, which can not be embedded into the PLC; the other is real-time performance of calculation, the solution strategy should meet the real-time requirements of the field. Therefore, the adaptive digital coordination strategy is proposed based on PLC.

3.1 The adaptive digital coordination strategy

As shown in Fig.8, the essence of the surfaces is a nonlinear binary function, i.e. \( N = f_i( P, H) \) and \( y = f_2( P, H) \). In order to simplify the calculation so that it can be applied in the PLC, the first order polynomial of the binary function is used for interpolation approximation.

The \( P-H \) coordinate plane can be obtained according to the operating range of VSU, and then it is divided into equal rectangles. The four vertices of any rectangle are \( S_i( P_1, H_1), S_2( P_2, H_2), S_3( P_3, H_3), S_4( P_4, H_4) \), which can be depicted as \( S_i( P_i, H_i) \) \( \{ i = 1, 2, 3, 4 \} \). The output value of the coordination controller corresponding to each vertex is \( Z_i( P_i, H_i) \) or \( Z_i( S_i) \). \( Z_i \) represents the rotational speed or guide vane opening. It can be given by:

\[
\begin{align*}
Z_1 &= a + bP_1 + cH_1 + dP_1H_1 \\
Z_2 &= a + bP_2 + cH_2 + dP_2H_2 \\
Z_3 &= a + bP_3 + cH_3 + dP_3H_3 \\
Z_4 &= a + bP_4 + cH_4 + dP_4H_4
\end{align*}
\]

(6)

Here, \( a, b, c, \) and \( d \) are the interpolated coefficients of corresponding rectangle. If the four vertices \( ( P_i, H_i) \) \( \{ i = 1, 2, 3, 4 \} \) of the rectangle are known, the value of \( Z_i \) can be obtained by looking up Fig.8 and Fig.9. These values i.e. \( P_i, H_i \), and \( Z_i \) are put into Equation (6) to calculate the interpolation coefficients.

According to the above method, the interpolation coefficients of all rectangular blocks can be calculated and stored in the PLC. If the input signals \( ( P, H) \) at a certain time is known, the position of the rectangular block can be found, then the four interpolated coefficients of the corresponding rectangular can be taken out, and then the output values \( ( N, y) \) can be calculated based on Equation (7).

\[
Z = a + bP + cH + dPH
\]

(7)

3.2 The main procedure

Step 1: Partition rectangular blocks. According to the field condition of the platform, the range of water head is set from 23 m to 33 m; the range of output power is set from 30 kw to 80 kW. The smaller the partition interval, the more accurate the calculation, but the greater the storage capacity of PLC. The grids can be shown in Fig.10.

Step 2: Find the output values \( ( N, y) \) corresponding to the vertices of each block. The relationship between \( ( N, y) \) and \( ( P, H) \) can be illustrated in Fig.8 and Fig.9. Section 2.3 is introduced to perform this step.

Step 3: Calculate the interpolated coefficients of each rectangular blocks based on Equation (6), and store these values in PLC.

Step 4: Read input signals \( ( P, H) \), retrieve position of block, take out the corresponding interpolation coefficients, and then calculate the output values \( ( N, y) \) based on Equations (7). It is noteworthy that if the input values falls exactly on the vertex of the block, we select the block at the bottom left as the current position.
The signal flows of the control system of VSU is illustrated in Fig.11, which shows that the coordination controller is the core of the control system of VSU. As shown in Fig.11, the coordination controller can receive the digital signals from the LCU, then follow the above steps to calculate the optimal speed and the GVO. The digital signal of optimal speed is transmitted to the converter for speed control; the digital signal of GVO is transmitted to the governor for opening control. Meanwhile, the coordination controller can be in manual mode, directly set the rotational speed and GVO to the converter and the governor.

4. Conclusions

A coordination controller of variable speed pumped storage unit is developed in this paper. Aiming at the coordinated control between governor and converter, the novel adaptive strategy of maximum efficiency point tracking is proposed. First, the optimal efficiency curves are described based on model experiment; and then the optimal operating curves of variable speed unit in the operation region is presented based on the BP neural networks; the convergence analysis of mean square error and
regression analysis are applied to verify the reliability of results. Aiming at applying the adaptive strategy of maximum efficiency point tracking to coordination controller, a new effective digital interpolation method is put forward, using programmable logic controller. The signal flows of the control system in variable speed unit are clarified. The proposed adaptive strategy can be easily applied in engineering, laying a good foundation for ensuring the efficient operation of variable speed units.

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