Research on power regulation of adjustable-speed pumped-storage system based on virtual head technology

Luyao Quan [a] [*], Jiayu You and Tong Jiang

School of electrical and Electronic Engineering, North China Electric Power University, Beijing, China

[*], [a] Corresponding author e-mail: quanlyddu@126.com

Abstract. Because the head of the traditional adjustable-speed pumped-storage system is relatively fixed during power regulation, the adjustable-speed pumped-storage system based on virtual head technology is proposed in this paper. Through the introduction of each device, the principle and the implementation method of virtual head technology and variable speed technology are analyzed.Aiming at the output characteristics of adjustable-speed pumped-storage generator-motor under different modes, the loud optimization process characteristics under pump and turbine running conditions is established respectively.

1. Introduction

Having overcomed the characteristics that the speed and power of the traditional pumped storage system is not adjustable, the traditional adjustable-speed pumped-storage system can provide a certain frequency automatic control capacity for the power system and optimize the operating performance of the two operating conditions of the pump turbine, so it is getting more and more popular [1-2].

The load of the grid connected hydro-generator units is usually given by the system, and it may change with the power balance of the power system at any time, especially for the peak-regulating units[1].In addition, the head of a power station often varies with seasons or different water storage stages, although the frequency of variation is not very high[1].Therefore, load and head are two main factors governing the load operation of hydropower units.

The traditional pumped storage system unit is always running at the fixed synchronous speed, whose power regulation means is to regulate the flow by controlling the opening of the turbine so as to regulate the power of the unit and make it accord with the given power index of the power system[2].However, when the head changes, this adjustment method often makes the running condition of the unit very unsatisfactory[2].Due to the use of AC excitation motor as a generator motor, the speed of traditional adjustable-speed pumped-storage system can be adjusted, so it has the function of automatically tracking the power of the pump water turbine, providing a certain frequency automatic control capacity for the power system, and improving the operating conditions of the pump turbine under two operating conditions.However, because it is still subject to relatively fixed head, the power regulation range is limited.

Studying a pumped storage unit that can change three parameters of pump turbine speed, flow rate and head can not only ensure the operation efficiency but also broaden the scope of power regulation,

which is of great significance to improve the unit operation efficiency and the frequency regulation capability.

2. The adjustable-speed pumped-storage system based on virtual head technology
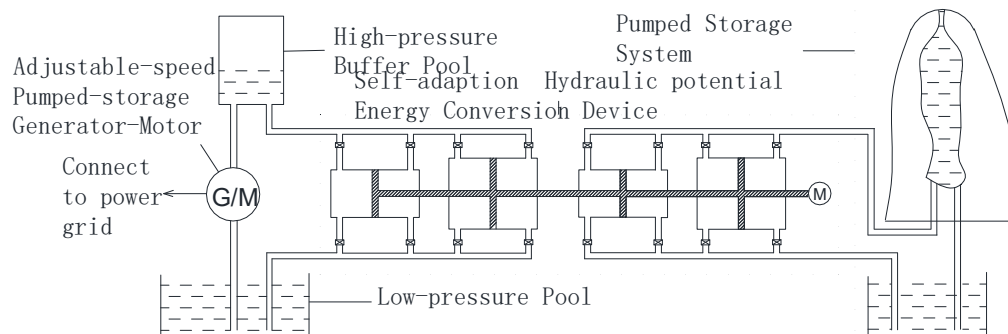

Figure 1. Schematic diagram of adjustable-speed pumped-storage system based on virtual head technology

Fig. 1 is a schematic diagram of the adjustable-speed pumped-storage system based on virtual head technology. The adjustable-speed pumped-storage generator-motor is connected with high-pressure buffer pool and the low-pressure pool respectively, which is also connected with the power grid. The first hydraulic cylinder group of the self-adaption hydraulic potential energy conversion device is respectively connected with the high-pressure buffer pool and the low-pressure pool, and the second hydraulic cylinder group of the self-adaption hydraulic potential energy conversion device are adaptable to the pumped storage system[3].

2.1. Variable speed technology
As with the traditional variable speed pumped storage system, Figure 2 showed the schematic diagram and the connection with the power grid of the adjustable-speed pumped-storage generator-motor in adjustable-speed pumped-storage system based on virtual head technology.The device is mainly composed of a pump turbine, a generator motor, a frequency converter and a control device. Among them, the pump turbine is the load or prime mover of the system, with its own mechanical governor. The generator motor is a doubly fed induction motor, which can operate in the power generation and electric state [4].The frequency converter provides AC excitation for the electric motor. When the rotor rotating frequency f_1 changing, the excitation current frequency f_2 is controlled to keep stator frequency f constant, thus $f = f_1 + f_2$, so as to realize variable speed and constant frequency operation of the motor[5].The control device is used to generate the given signal of power, speed and guide vane opening, which is used to control the inverter, governor and guide vane respectively.
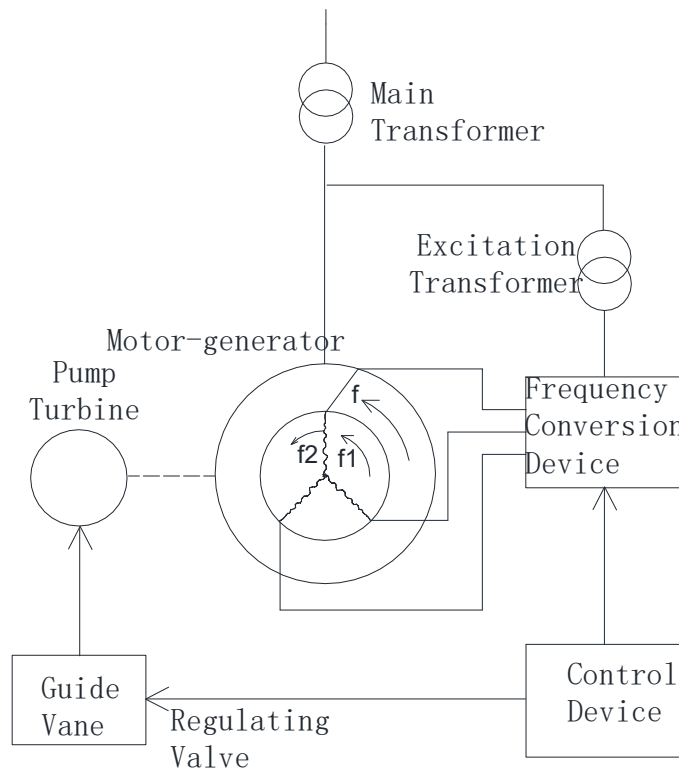
Figure 2. Schematic diagram of adjustable-speed pumped-storage generator-motor

2.2. Virtual head technology

Compared with the traditional adjustable-speed pumped-storage system, the self-adaption hydraulic potential energy conversion device and the high-pressure buffer pool are added to the system. The high-pressure buffer pool provides a virtual head through using a closed container with pressure-adjustable compressed air. The adjustment method can be filling or exhausted air into the closed container by the compression expander. The self-adaption hydraulic potential energy conversion device is composed of the first hydraulic cylinder group, the second hydraulic cylinder group, the valve, the piston, the motor and the auxiliary unit of running parameter measurement. Through the opening and closing of the valve, the adaptive hydraulic potential energy conversion device can achieve the energy conversion between the potential energy of the high-pressure buffer pool and the low-pressure pool and the potential energy formed by pumped storage system. Therefore, the head of the system can be changed according to the power condition.

3. Optimization analysis of load characteristics under pump operating conditions

3.1. Pump characteristic analysis

When the pump water turbine running in the pump mode, the performance curves of the pump frequency, that is head-flow, power-flow efficiency-flow , are close to the parabolic shape [6,7], which can be solved by least squares method using polynomial curve fitting[9]. The performance curve fitting equation of the pump frequency conversion is as follows [5]

$$H = A_0 n^2 + A_1 nQ + A_2 Q^2 \tag{1}$$

$$N_p = B_0 n^3 + B_1 n^2 Q + B_2 nQ^2 \tag{2}$$

$$\eta_p = \frac{C_0}{n}Q + \frac{C_1}{n^2}Q^2 + \frac{C_2}{n^3}Q^3 \tag{3}$$

Where, n, Q, H are the speed(the unit is r/min), flow rate (the unit is m/s^3)and effective lift(the unit is m)of the pump respectively. η_p is the efficiency of pump and N_p is the pump shaft power(the unit is kW).

According to the characteristics of the pump, the relationship between pump outlet power N_e with pump head and flow is as follows: the power relationship can be expressed as:

$$N_p = \frac{N_e}{\eta_p} \tag{4}$$

$$N_e = \gamma QH \tag{5}$$

Where, N_e is the pump outlet power and γ is the proportion of water, and its value is $9.81N/m^3$.

3.2. Load characteristics process under electric condition
According to the pump characteristic analysis above, optimal regulation can be achieved aimed at the real-time power instruction and optimal efficiency. The main steps of the regulation process are as follows:

(1) From formulas (2), the relationship between the given total input power N_p and pump speed n and flow rate Q can be obtained $N_p = f_1(n, Q)$.

(2) From formula (3), the relationship between the unit's total efficiency under pump mode and pump speed n, flow rate Q can be obtained $\eta_p = f_2(n, Q)$.

(3)According to the given input power N_0 of the power grid , When $N_0 = f_1(n, Q)$ and the efficiency of variable speed Pumping-storage unit reaches its maximum value, the speed and flow of the unit can be calculated from $N_p = f_1(n, Q)$ and $\eta_p = f_2(n, Q)$.

(4) According to the value of pump speed and flow obtained from step (3), the head of the pump H is obtained from formula (1) when the pump efficiency is maximized. At this time, the efficiency of the adjustable-speed pumped-storage generator-motor is the highest.

4. Optimization analysis of load characteristics under turbine operating conditions

4.1. Turbine characteristic analysis
According to the knowledge of water turbines, in order to characterize the hydraulic turbine characteristics of each wheel system, it is usually stipulated that the experimental results of the model are converted to the diameter of the wheel $D_1 = 1m$, and the effective water head $H = 1m$, that is, unit parameters, as a common measure of [7]. Unit speed n_{11} and unit flow Q_{11} are expressed as [7]:

$$n_{11} = \frac{nD_1}{\sqrt{H}} \tag{6}$$

$$Q_{11} = \frac{Q}{D_1^2 \sqrt{H}} \tag{7}$$

Where, n, Q, H are the speed(the unit is r/min), flow rate (the unit is m/s^3)and effective lift(the unit is m)of the pump respectively. N_t is the pump shaft power(the unit is kW). D_1 is the diameter of the runner (the unit is m).

According to reference [10], turbine efficiency can be expressed as a polynomial function of unit speed and unit flow rate.

$$\eta_t(n_{11}, Q_{11}) = \frac{1}{2}\left[\left(\frac{90}{\lambda} + Q_{11} + 0.78\right)exp\left(-\frac{50}{\lambda}\right)\right] \times 3.33Q_{11} \tag{8}$$

Where, $\lambda = \left(\frac{1}{\lambda_i + 0.089} - 0.0035\right)^{-1}$ and $\lambda_i = \frac{RA_r n_{11}}{Q_{11}}$ respectively are the radius of the turbine impeller(the unit is m) and the area swept by the impeller when it rotates(the unit is m^2).

The power relationship of the adjustable-speed pumped-storage generator-motor can be expressed as:
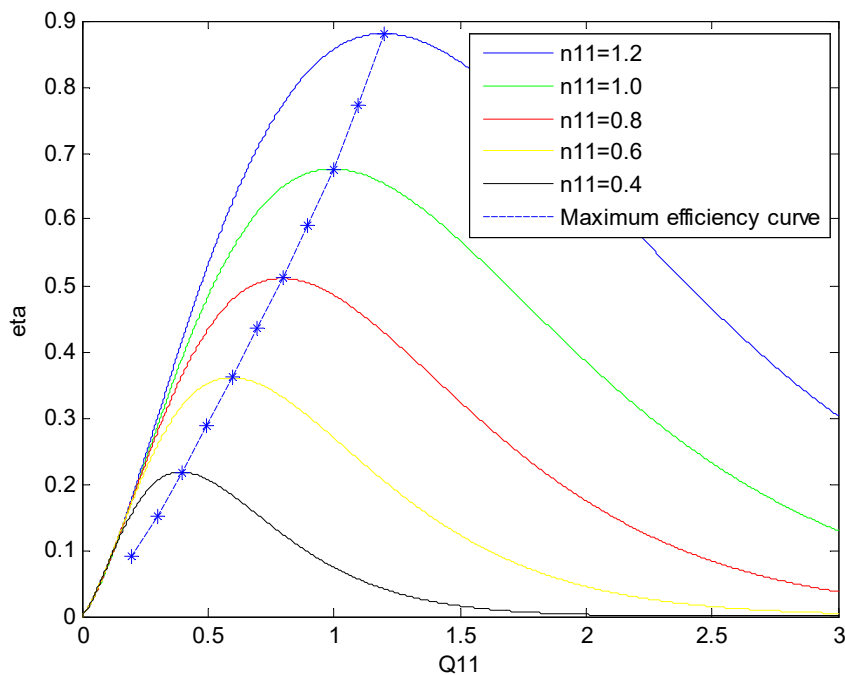
$$N_t = N_e \eta_t \tag{9}$$

Figure 3. The curves of turbine efficiency under different unit

The curves of turbine efficiency η_t under different unit flow with unit speed changes are shown in Fig. 3.As can be seen from Fig. 5, the unit flow rate will change with the maximum unit efficiency at different unit speeds.When the unit speed deviating from the optimal unit speed, the efficiency of the turbine will decrease, the coefficient of cavitation erosion increases, and the wear and vibration of the turbine increase, which eventually leads to the deterioration of the operating conditions of the system.

Therefore, on the premise of meeting the unit output requirements, when the unit runs along the optimal efficiency trajectory, the efficiency is the highest. On this basis, the load optimization process of hydraulic turbine model is proposed.

4.2. Load characteristics process under power generation condition
(1) From Fig. 3, the optimal efficiency trajectory function of adjustable-speed pumped-storage generator-motor under power generation Condition $\eta_{T\max} = g_2(Q_{11})$ is obtained.

(2) According to formula (6) and the optimal efficiency trajectory function obtained from step (1), the relationship between the given input power $N_t = N_e \eta_{T\max}$ and turbine unit speed and unit flow ratecan be obtained $N_t = g_3(Q_{11}, H)$.

(3) According to the given input power N_0 of the power grid , When $N_0 = g_3(Q_{11}, H)$ and the optimal efficiency of variable speed Pumping-storage unit η_{Tmax} reaches its maximum value, the speed and flow of the unit can be calculated from $N_t = g_3(Q_{11}, H)$ and $\eta_{T\max} = g_2(Q_{11})$.

(4) According to the value of unit flow Q_{11} and unit head H of a hydraulic turbine calculated by step (6), the unit speed n_{11} and speed n of the turbine can be obtained from $\eta_t = g_1(Q_{11}, n_{11})$ and formula (10).

(5) According to the value of unit flow Q_{11} and unit head H of a hydraulic turbine calculated by step (3), the Formula (7) is used to obtain the flow rate of the turbine when the unit efficiency is maximized.

5. Conclusion
In this paper, the composition of adjustable-speed pumped-storage system based on virtual head technology is introduced in detail. The principle and realization method of virtual head technology and variable speed technology are analyzed theoretically. Based on the characteristics of the proposed system, the load optimization process of pump operation and turbine operation is proposed. Having a higher efficiency and larger range of power regulation, the system proposed in this paper is conducive to play the role of pumped storage system in network in cycle loading and frequency modulation as the pumped storage system. And because of the improvement of efficiency, cavitation erosion, wear reduction and vibration of pump turbine are improved. The operation stability of the unit is relatively improved, and the stable operation range is enlarged, which makes the operation of the unit more reliable and flexible [2,5]. Further research on power regulation control strategy and system optimal regulation strategy based on this paper is still worth carrying out.

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