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# Energy efficiency test and analysis of large hydro-generators based on economic evaluation

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**Abstract**. A new evaluation method was proposed for the determination of economic operation zone of large hydrogenerators. Firstly, a large number of test data were obtained by carrying out efficiency tests of the turbine at different heads. Secondly, through data analysis, the value method of $K_0$ and the water consumption rate were constructed to determine the economic operation zone and the optimal economic operation zone, separately. Thirdly, the validity of the proposed method was verified by applying to an actual hydrogenerator. Compared with traditional methods, this method can be used to guide the economic operation of hydropower plants.

## 1. Introduction

The efficiency test of hydraulic turbines, especially, the prototype turbines is one of the bases for the economic operation of the hydropower plant and even the entire power grid. This test can show the operation status of the turbine, and thus provide technical data for maintenance and renovation. Through adjustment, the turbine can operate in the high efficiency zone, which can make full use of hydraulic resources and improve the economic benefits of the power plant. So this test can also be used to guide the economic operation of the hydraulic unit and even the power grid. The current unit capacity and dimension of turbines are large, and giant generating set of megawatts has been developed in China. There will be large errors to simulate the prototype hydraulic turbine under laboratory conditions, so the performance of the turbine has to be determined by field efficiency test. On the other hand, the turbine performance is changing with the actual operating conditions. The flow components of the turbine will be worn after running for a long time. Together with cavitation, vibration, sediment erosion and other factors, the turbine efficiency will be reduced. Large errors will be generated if guiding the operation of the turbine according to the model efficiency test results. The correct evaluation of the dynamic characteristics of the unit is an important measure to guarantee its safe and economic operation. For better economic benefits, the dynamic characteristics of turbine units are used more and more to guide their economic operation.

By taking a large hydrogenerator as the example, the $K_0$ value method and the water consumption rate method were used to evaluate the energy efficiency of the unit. This method has the characteristics of simple, easy to understand, reliable and high precision, and it is suitable for large hydrogenerators.

## 2. Physical model and Numerical methods

The entire Economic evaluation is necessary to bring the unit's full potential into play, improve the utilization rate of water energy, and gain greater benefits with less resource efficiency.

The turbine efficiency can be calculated after obtaining the power output, flow rate and head of the turbine. The formula is as follows:

$$\eta_T = \frac{N_T}{\rho g Q H} \times 100\% \tag{1}$$

Where, $\eta_T$ is the turbine efficiency (%); $N_T$ is the turbine output power (MW); $\rho$ is the water density (kg/m$^3$); $g$ is the local gravity acceleration (m/s$^2$); $Q$ is the flow rate (m$^3$/s); and $H$ is the operating head (m).

### *2.1. $K_0$ Value Method (Determination of Economic Operation Zone)*

The active power of the unit can be expressed as $P_n = K_0 Q H = \rho \eta g Q H$ .

Where, $K_0 = \rho \eta g$ , $\eta$ is the efficiency of the unit. The value of $K_0$ can be selected by experience: 8.5 for giant units, 8.0～8.5 for large units, and 7.5～8.0 for medium units.

### *2.2. Water Consumption Rate Method (Determination of Optimal Economic Operation Zone)*

The water consumption rate is the amount of water consumed for generating unit capacity, denoted by $\boldsymbol{q_0}$, uint is m$^3$/kWh.

$$q_0 = \frac{3600Q}{P_g} = \frac{3600Q}{\rho g H \eta_G \eta_T} \tag{2}$$

Where, $Q$ is the measured flow rate, $P_g$ is the power of generator, $\eta_G$ is efficiency of the generator (%), and $\eta_T$ is efficiency of the turbine (%).

The main factors affecting the water consumption rate is the turbine efficiency and the operating head. Under the same conditions, the higher the efficiency, the lower the water consumption rate. The changing pattern of the water consumption rate can be fitted, and the lowest point (the minimum water consumption rate) on the curve can be calculated. And then, the water consumption rates at ±1% of the lowest point are taken as the optimal economic operating zone.

## 3. Results and discussions

Basic Parameters of a Large Unit:
Generator model: SF600-48/14200 Rated capacity: 667 MW
Rated speed: 125 r/min Power factor: 0.9
Rated head: 154.6 m Type of cooling: air-cooling
Turbine model: HLF600R-LJ-620
Rated output: 611 MW Maximum output: 679 MW
Rated speed: 125 r/min Rated flow rate: 431.7 m$^3$/s
Table 1 shows test points at various water levels.

**Table 1.** Test points at various water levels from ▽790 m to ▽850 m.

| No. | Measured upstream water level (m) | Measured downstream water level (m) | Water head at the power station (m) |
|---|---|---|---|
| 1 | 788.70 | 669.10 | 119.60 |
| 2 | 796.39 | 668.86 | 127.53 |
| 3 | 805.35 | 669.39 | 135.96 |
| 4 | 815.20 | 670.44 | 144.76 |
| 5 | 824.73 | 673.57 | 151.16 |
| 6 | 831.70 | 670.92 | 160.78 |
| 7 | 834.90 | 672.31 | 162.59 |

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| 4 | 815.20 | 670.44 | 144.76 |
| 5 | 824.73 | 673.57 | 151.16 |
| 8 | 839.60 | 669.74 | 169.86 |
| 9 | 844.60 | 671.76 | 172.84 |
| 10 | 849.50 | 671.67 | 177.83 |

**Table 2.** Values $K_0$ at different heads.

| 119.80m | | 127.79m | | 136.75m | | 144.80m | | 153.53m | | 161.17m | | 163.16m | | 168.40m | | 173.22m | | 178.46m | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Active power (MW) | $K_0$ value | Active power (MW) | $K_0$ value | Active power (MW) | $K_0$ value | Active power (MW) | $K_0$ value | Active power (MW) | $K_0$ value | Active power (MW) | $K_0$ value | Active power (MW) | $K_0$ value | Active power (MW) | $K_0$ value | Active power (MW) | $K_0$ value | Active power (MW) | $K_0$ value |
| 54.61 | 5.22 | 100.11 | 6.43 | 122.86 | 7.04 | 139.58 | 7.18 | 137.91 | 7.22 | 163.01 | 7.42 | 199.47 | 7.80 | 184.19 | 7.64 | 207.63 | 7.82 | 199.08 | 7.78 |
| 91.50 | 6.24 | 140.04 | 7.54 | 165.71 | 7.83 | 196.10 | 8.06 | 213.42 | 8.15 | 244.63 | 8.35 | 275.55 | 8.52 | 285.10 | 8.63 | 308.51 | 8.65 | 297.84 | 8.53 |
| 140.24 | 7.19 | 208.07 | 8.41 | 222.00 | 8.50 | 253.09 | 8.57 | 276.75 | 8.71 | 328.28 | 8.87 | 314.65 | 8.76 | 324.42 | 8.77 | 370.70 | 8.98 | 357.31 | 8.90 |
| 186.29 | 8.01 | 266.43 | 8.95 | 262.33 | 8.78 | 317.34 | 8.91 | 353.16 | 9.01 | 386.87 | 9.13 | 417.94 | 9.09 | 409.04 | 9.08 | 427.35 | 9.12 | 434.18 | 9.14 |
| 262.82 | 8.59 | 306.41 | 8.99 | 324.20 | 9.00 | 377.20 | 9.11 | 408.90 | 9.14 | 455.70 | 9.23 | 476.54 | 9.23 | 476.64 | 9.21 | 491.57 | 9.26 | 470.86 | 9.15 |
| 314.00 | 8.74 | 349.49 | 9.16 | 385.89 | 9.17 | 444.55 | 9.30 | 476.26 | 9.27 | 510.96 | 9.30 | 540.76 | 9.32 | 530.11 | 9.32 | 534.04 | 9.31 | 521.62 | 9.25 |
| 347.89 | 8.79 | 389.65 | 9.22 | 434.40 | 9.23 | 463.57 | 9.33 | 516.36 | 9.28 | 553.10 | 9.25 | 560.89 | 9.29 | 571.45 | 9.30 | 572.40 | 9.34 | 555.78 | 9.31 |
| 369.28 | 8.63 | 408.92 | 9.29 | 453.91 | 9.20 | 486.48 | 9.35 | 541.08 | 9.24 | 576.89 | 9.21 | 588.92 | 9.26 | 592.71 | 9.28 | 593.29 | 9.33 | 583.49 | 9.35 |
| 398.28 | 8.62 | 433.03 | 9.19 | 479.83 | 9.14 | 522.23 | 9.31 | 580.08 | 9.12 | 605.08 | 9.17 | 611.33 | 9.19 | 613.04 | 9.24 | 613.96 | 9.30 | 611.29 | 9.33 |

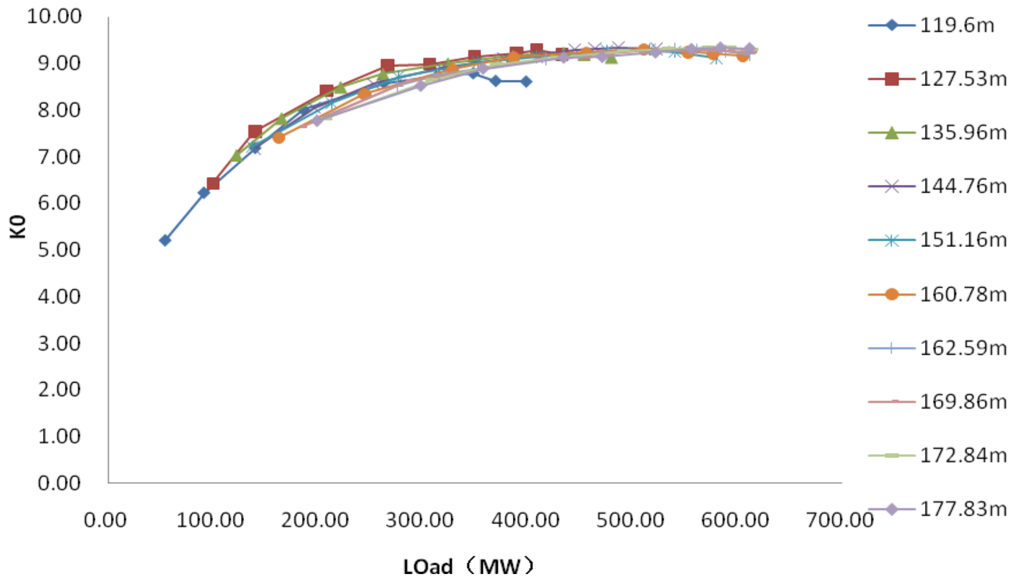


**Figure 1.** Variation trend of $K_0$ at different loads

According to the characteristics of the unit, table 2 and figure 1, $K_0$=9 is taken as the basis to determine the zone. The economic operating zone of unit 3 is listed in table 3.

**Table 3.** Economic operating zone of the unit (according to the head).

| Head at the power station (m) | 119.6 | 127.53 | 135.96 | 144.76 | 151.16 | 160.78 | 162.59 | 169.86 | 172.84 | 177.83 |
|---|---|---|---|---|---|---|---|---|---|---|
| Economic operating zone (MW) | - | 280～430 | 300～480 | 330～520 | 340～580 | 355～600 | 375～600 | 385～600 | 400～600 | 400～600 |

It can be seen from table 2, table 3 and figure 1 that with the increasing of the head, the economic operating zone moves up and widens. There is no economic operating zone at the ultra low water head, while the economic operating zone is the widest near the rated head.

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**Table 4.** Water consumption rates at different heads.

| 119.6m | | 127.53m | | 135.96m | | 144.76m | | 151.16m | | 160.78m | | 162.59m | | 169.86m | | 172.84m | | 177.83m | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Active power (MW) | WCR | Active power (MW) | WCR | Active power (MW) | WCR | Active power (MW) | WCR | Active power (MW) | WCR | Active power (MW) | WCR | Active power (MW) | WCR | Active power (MW) | WCR | Active power (MW) | WCR | Active power (MW) | WCR |
| 54.61 | 5.83 | 100.11 | 4.55 | 122.86 | 3.84 | 139.58 | 3.55 | 137.91 | 3.33 | 163.01 | 3.07 | 199.47 | 2.89 | 184.19 | 2.85 | 207.63 | 2.70 | 199.08 | 2.64 |
| 91.50 | 4.88 | 140.04 | 3.88 | 165.71 | 3.45 | 196.10 | 3.17 | 213.42 | 2.95 | 244.63 | 2.73 | 275.55 | 2.64 | 285.10 | 2.52 | 308.51 | 2.44 | 297.84 | 2.41 |
| 140.24 | 4.23 | 208.07 | 3.48 | 222.00 | 3.18 | 253.09 | 2.98 | 276.75 | 2.76 | 328.28 | 2.57 | 314.65 | 2.57 | 324.42 | 2.48 | 370.70 | 2.35 | 357.31 | 2.30 |
| 186.29 | 3.80 | 266.43 | 3.27 | 262.33 | 3.07 | 317.34 | 2.86 | 353.16 | 2.67 | 386.87 | 2.50 | 417.94 | 2.48 | 409.04 | 2.40 | 427.35 | 2.32 | 434.18 | 2.25 |
| 262.82 | 3.54 | 306.41 | 3.26 | 324.20 | 3.00 | 377.20 | 2.80 | 408.90 | 2.63 | 455.70 | 2.47 | 476.54 | 2.44 | 476.64 | 2.36 | 491.57 | 2.28 | 470.86 | 2.24 |
| 314.00 | 3.48 | 349.49 | 3.20 | 385.89 | 2.95 | 444.55 | 2.74 | 476.26 | 2.60 | 510.96 | 2.45 | 540.76 | 2.42 | 530.11 | 2.34 | 534.04 | 2.27 | 521.62 | 2.22 |
| 347.89 | 3.46 | 389.65 | 3.17 | 434.40 | 2.92 | 463.57 | 2.74 | 516.36 | 2.59 | 553.10 | 2.47 | 560.89 | 2.42 | 571.45 | 2.34 | 572.40 | 2.26 | 555.78 | 2.20 |
| 369.28 | 3.52 | 408.92 | 3.15 | 453.91 | 2.93 | 486.48 | 2.73 | 541.08 | 2.61 | 576.89 | 2.48 | 588.92 | 2.43 | 592.71 | 2.35 | 593.29 | 2.27 | 583.49 | 2.19 |
| 398.28 | 3.53 | 433.03 | 3.19 | 479.83 | 2.95 | 522.23 | 2.74 | 580.08 | 2.64 | 605.08 | 2.49 | 611.33 | 2.45 | 613.04 | 2.36 | 613.96 | 2.27 | 611.29 | 2.20 |

Note: WCR refers to the water consumption rate

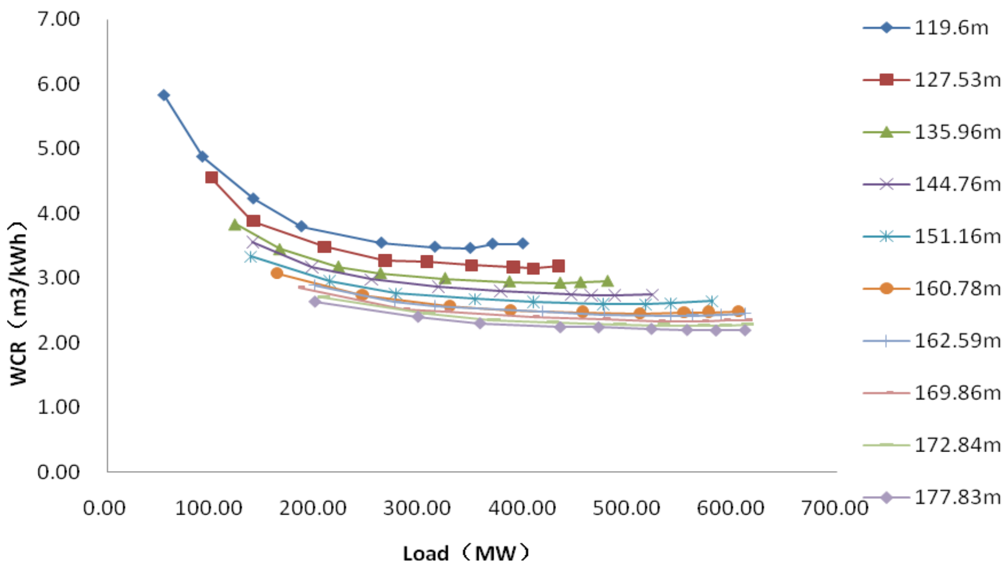


**Figure 2.** Variation trend of fitted water consumption rates at different loads

According to the characteristics of the unit, the water consumption rates at ±1% of the lowest water consumption rate are taken as the basis to determine the zone. The optimal economic operating zone of unit 3 is listed in table 5.

**Table 5.** Optimal operating zone of the unit (according to the head).

| Head at the power station (m) | 119.6 | 127.53 | 135.96 | 144.76 | 151.16 | 160.78 | 162.59 | 169.86 | 172.84 | 177.83 |
|---|---|---|---|---|---|---|---|---|---|---|
| Optimal operating zone (MW) | 280～320 | 330～380 | 380～420 | 450～500 | 500～550 | 550～600 | 550～600 | 550～600 | 550～600 | 550～600 |

It can be seen from table 4, table 5 and figure 2 that with the increasing of the head, the optimal economic operating zone also moves up, but the range maintains at about 50 MW. The optimal economic operating zone remains the same at above the rated head.

## 4. Conclusions

Based on the characteristics of large hydraulic turbines, the extreme areas of $K_0$ value and water consumption rate are constructed to determine the economic operating zone and the optimal economic operating zone of the turbine by using the results from the full head efficiency tests.

The value method of $K_0$ and the water consumption rate have a simple principle, and are easy to understand and use.

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The method proposed in this paper to determine the economic operating zone and the optimal economic operating zone is a summary of experience in field practices, which has guiding significance and reference value for the economic operation of large hydro-generators.

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