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To cite this article: Xiankui Wen et al 2019 IOP Conf. Ser.: Earth Environ. Sci. 237 062045

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3D Surface Fitting Method for Efficiency of Turbine Generator Set Based on Real-time Dynamic Correction

Xiankui Wen\textsuperscript{1*}, Chunhe Shen\textsuperscript{1}, Cheng Mao\textsuperscript{1} and Li Su\textsuperscript{1}

\textsuperscript{1} Electric Power Research Institute of Guizhou Power Grid Co., Ltd. Guiyang, Guizhou, 550002, China

\*Corresponding author’s e-mail: 13985410224@139.com

Abstract. The three-dimensional curved surface of "working head-output-efficiency" of turbine generating set needs to be modified dynamically in real time because of the small amount of data at the initial stage of measurement and the change of efficiency after long-term operation. A data preprocessing method is presented. The processed sample data can not only filter out the measurement noise, but also track the real efficiency change of the turbine generator set. Three correction conditions have been worked out, and the three-dimensional curved surfaces will be corrected after the correction conditions are satisfied. The field demonstration project proves that it can ensure the accuracy of efficiency curved surface of turbine generator set and provide accurate data for optimal load distribution.

1. Introduction

Hydroelectric power is a clean renewable energy and has developed rapidly in recent years. For multiple units in operation, the optimal load distribution can be made according to their respective efficiency curves, and the utilization ratio of water energy can be improved by making full use of the high efficiency area of the units\cite{1}.

Efficiency of turbine generator set is a nonlinear function of output, working head and flow of turbine. Data fitting method is used to approximate the function relationship. At present, the main methods used are least square method and its improved algorithm, cubic spline function method, Akima interpolation method, three-dimensional general polynomial least squares method and so on\cite{2~6}. According to the test data, the three-dimensional surface of the "working head-output-efficiency" is fitted. In the actual measurement, because the change of working head is not very much, extrapolating the data under other working heads will bring great errors; and with the long-term operation of the unit, its operating conditions will change, so a method is needed to ensure the accuracy of the curved surface, that is, through real-time monitoring a large number of operating data of the unit and carrying out Real time dynamic correction. It provides accurate data support for achieving optimal load distribution.

2. Surface fitting method

Through the analysis of the commonly used fitting methods, it is decided to use the "three-dimensional general polynomial least squares method" for fitting. Its advantage is that the polynomial coefficients can be obtained by requiring a small number of unit output data and data under different working heads. Theoretically, this method only needs 10 groups date of “working head-output-efficiency” with a certain degree of dispersion.Unit efficiency can be obtained at any output, any working head, any operating condition. The more data there is, the higher is the precision and the smaller is the error.
Three-dimensional general polynomial least squares method regards units efficiency as a 4-degree polynomial function of working head and units output, the following equations are established:

$$\xi = a_1x^2y^2 + a_2x^2y + a_3xx + a_4xy + a_5x + a_6y^2 + a_7y + a_8$$  \hspace{1cm} (1)

In Formula (1), \( x \) is the working head and the units of measurement is metre, \( y \) is the unit output and the units of measurement is MW, \( \xi \) is the efficiency of the turbine generator set and the units of measurement is \%, \( a_1, a_2, \cdots, a_8 \) is the coefficient.

By applying the fitting model of the three-dimensional surface of "working head-output-efficiency", the measured data samples \((x, y, \xi)\) are input into the model, and the coefficients \((a_1, a_2, \cdots, a_8)\) are obtained by using the least square method to control the errors, so that the unit efficiency at any point of output, working head and working condition can be obtained.

In the initial stage of system operation, the collected data are not sufficient, and the accumulated "working head-output-efficiency" samples are not many. However, under the condition of a small number of samples (the samples can be obtained either by on-line automatic system automatic measurement or by off-line test), the "three-dimensional general polynomial least squares method" can be used to obtain an approximate three-dimensional model of "working head-output-efficiency". Although the model has some errors, the optimal load distribution is still carried out by this model.

3. Real time dynamic correction

When the sample size of the system has a certain accumulation or satisfies the timing condition or exceeds the error control condition, the program automatically re-fits the calculation to correct the error of the previous model, and obtains a new and more accurate three-dimensional model about "working head-output-efficiency".

3.1. Data preprocessing

With the increase of accumulative samples, the same or similar working conditions of the sample data will be more and more, correspondingly, even under the same working conditions (such as working head, output, etc.), the actual measured unit efficiency data may be different. The reason is that besides the measurement error noise, the actual efficiency of the unit has also changed (for example, the runner cavitation causes the turbine efficiency to decline).

Therefore, in the process of fitting calculation, it is necessary to pretreat the sample data, obtain a sample data which can filter out the measurement noise and reflect the real efficiency change of the unit, and then use the data after pretreatment to fit the calculation, as follows:

Sort out the sample data. At the same time, it satisfies the following formula:

$$x_i - \Delta x \leq x_i \leq x_i + \Delta x$$  \hspace{1cm} (2)

$$y_i - \Delta y \leq y_i \leq y_i + \Delta y$$  \hspace{1cm} (3)

In Formula (2), \( x_i \) is the measured values of working head and the units of measurement is metre, \( x_i \) is the working head values in the model and the units of measurement is metre, \( \Delta x \) is the working head error, set to 0.1M.

In Formula (3), \( y_i \) is the measured values of output and the units of measurement is MW, \( y_i \) is the output values in the model and the units of measurement is MW, \( \Delta y \) is the output error, Set to 0.1% of the rated load of the unit.

Then the efficiency data consisting of the output and the working head constitute a time series function. We define this function formula as follows:
In formula (4), $W_i$ is the weight function of efficiency data at different times. It is expressed in the following formula:

$$
\xi = \sum_{i=1}^{n} W_i \cdot \xi_i \\
i = 1...n
$$

In formula (4), $W_i$ is the weight function of efficiency data at different times. It is expressed in the following formula:

$$
W_i = \begin{cases} 
1 - \frac{e^{(t_0 - t_i)/m}}{10000} \\
0 \text{ (when } \frac{e^{(t_0 - t_i)/m}}{10000} \geq 1.0) 
\end{cases}
$$

In formula (5), $t_0$ is the initial date and the unit is the day, $t_i$ is the date corresponding to the efficiency sample and its unit is the day.

In formula (5), $m$ is an adjustable coefficient, which means that the contribution of efficiency data to $e$ under the same operating condition, for example, when $m = 4$, means that the contribution of efficiency sample data 40 days ago to the fitting surface is close to 0. The larger the $m$ value, the smaller the attenuation of the contribution of historical data to the surface fitting. The maximum value of the weight function is 1.0, and the minimum value is 0.0. When the value is 0, it means that the data does not participate in the calculation and has no contribution to the final value.

3.2. Control conditions for real-time dynamic correction

There are three conditions for automatic restart fitting calculation.

3.2.1. Calibration condition 1: cumulants of sample size

When the number of samples increases to a certain number (for example, 500), the fitting is done again.

Record $N_p$ as the cumulative sample number of the previous fitting calculation, $N_r$ as the current cumulative sample number, when $N_r - N_p \geq \Delta N$, the program automatic restart fitting calculation to correct the error of the previous model, where $\Delta N$ is the minimum set value of sample increment.

3.2.2. Calibration condition 2: calculation period

When new samples are accumulated for a certain period (e.g. one month), the program automatic restart fitting calculation to correct the error of the previous model, and obtains a new three-dimensional model about working head-output-efficiency.

3.2.3. Calibration condition 3: error control

$\xi_e(a_1, a_2, \cdots, a_6)$ is set as the coefficient of the three-dimensional model about “working head-output-efficiency” in the previous fitting calculation.

According to formula (1), the measured working head ($x$) and unit output ($y$) are brought into the formula to calculate the estimated unit efficiency.

Set $\xi_r$ for actual measurement of unit efficiency, then the correction condition can be expressed in the following formula:

$$
|\xi_r - \xi_e| \geq 2E_e
$$

(6)
In formula (7), \(t_0\) is the initial date and the unit is the day, \(E_p\) is the maximum error between all the sample points in the first fitting calculation and ideal surfaces. \(E_i\) is an acceptable maximum allowable error between the estimated unit efficiency and the measured efficiency, which can generally be set at 0.5% ~ 1.0%. If formula (6) is satisfied, it is determined that the error of the previous model is large, and the program automatically re-fits the calculation to correct the error of the previous model, thus obtaining a new and more accurate three-dimensional model about “working head-output-efficiency”.

3.3. Real-time dynamic correction
When the real-time test sample meets the correction condition, the three-dimensional general polynomial least squares method is used to modify the three-dimensional surface model of "working head-output-efficiency". The whole real-time dynamic correction process is shown in Figure 1.

![Figure 1. Real-time dynamic correction process](image)

4. demonstration project
The project is demonstrated at Hongfeng power plant in Guizhou. The parameters of the unit are shown in Table1:

| serial number | parameter name | numerical value |
|---------------|----------------|-----------------|
| 1             | rated head     | 142 m           |
| 2             | rated discharge| 36.84 m³        |
| 3             | rated capacity | 45 MW           |

After half a year's operation, three-dimensional surface fitting models about “working head-output-efficiency “have been obtained as follows:
\[ \xi = 0.0012447609019855x^2y^2 + (-0.035647797777857)xy + \\
0.13635783193979x^2 + (-0.15843435948454)xy + \\
4.5293968408455xy + (-19.189865214118)x + \\
4.7960201554886y^2 + (-136.17590062848)y + \\
683.13225 \]

Automatically draw the "working head-output-efficiency" 3D surface as shown in Figure 2. According to the fitting surface, the relation curve between output and efficiency under different working head can be plotted (Equal working head curve), as shown in Figure 3. The relation curve between working head and efficiency under different output can be plotted (Equal output curve), as shown in Figure 4. The relation curve between working head and output under different efficiency can be plotted (Equal efficiency curve), as shown in Figure 5.

5. Conclusions
After a long-term real-time monitoring unit operation data, the monitoring data are pre-processed to obtain a sample data which can filter out the measurement noise and reflect the real efficiency changes of the unit.
After satisfying the three conditions of model correction, real-time dynamic correction is carried out automatically to ensure the accuracy of the three-dimensional surface of "working head-output-efficiency".

The method presented in this paper has been verified by a demonstration project and can provide accurate data support for optimal load distribution.

Acknowledgments
This work was financially supported by Guizhou province science and technology major project([2014]6022).

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