

Assess and Predict Automatic Generation Control Performances for Thermal Power Generation Units Based on Modeling Techniques

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Abstract. Automatic generation control(AGC) is a key technology to maintain real time power generation and load balance, and to ensure the quality of power supply. Power grids require each power generation unit to have a satisfactory AGC performance, being specified in two detailed rules. The two rules provide a set of indices to measure the AGC performance of power generation unit. However, the commonly-used method to calculate these indices is based on particular data samples from AGC responses and will lead to incorrect results in practice. This paper proposes a new method to estimate the AGC performance indices via system identification techniques. In addition, a nonlinear regression model between performance indices and load command is built in order to predict the AGC performance indices. The effectiveness of the proposed method is validated through industrial case studies.

1. Introduction

The technology of automatic generation control(AGC) is paramount important for safe and efficient operations of power grid [1-2]. A balance of required powers from users and the generated powers is crucial to achieve a stable grid frequency and a good quality of power supply. Hence, power generation units must regulate their actual power outputs according to the required power outputs distributed by electric dispatching automation systems from power grid control centers [3-8].

For the aim of measuring the contribution of each power generation unit, a set of AGC performance assessing criteria have been proposed. In particular, an official document titled “*Detail operation and management rules for North China regional power plants*” was proposed by North China Electric Power Supervision Bureau. The rules have specified the following AGC performance indices, namely, regulation speed, adjustment accuracy and response time, denoted by K_1 , K_2 and K_3 respectively. The weighted average of K_1 , K_2 and K_3 is regarded as an overall measurement of AGC performances. The current method to calculate these indices is to read some particular data samples from AGC responses. However, this method is severely affected by measurement noises and is only feasible for step-type responses. As a result, such a method will lead to incorrect estimated performance indices in practice.

In this paper, a new method is proposed to estimate and predict AGC performance indices of power generation units. The indices K_1 , K_2 and K_3 are estimated based on a dynamic mathematical model that is identified from collected data samples through system identification techniques. The required generated power is regarded as the model input, and the actual generated power is taken as the model output. The identified model is transformed into a first-order linear time-invariant continuous-time model with time delays. Parameters of the continuous-time model are used to compute the AGC



performance indices K_1 , K_2 and K_3 . The AGC performance indices are predicted based on a fitted curve between a set of actual generated powers and the corresponding indices K_1 , K_2 and K_3 .

The rest of this paper is organized as follows. Section 2 introduces the AGC performance indices. Section 3 presents the method to estimate and predict the AGC performance indices. Section 4 provides industrial case studies to illustrate the effectiveness of the proposed method. Section 5 makes some concluding remarks.

2. AGC performance indices

A standard AGC response of a power generation unit is illustrated in Figure 1. The symbols $P_{\min, i}$ and $P_{\max, i}$ denote the lower and upper limits of the generated active power, and P_{di} is the critical power when a coal mill is at the start or shutdown status. The whole response in Figure 1 can be described as follow. Before the time instants T_0 and T_1 , the unit stays at a steady-state condition with the generated active power P_1 . At the time instant T_0 , the unit receives an AGC command to raise the unit output to P_2 . The generated active power starts the response to the command at the time instant T_1 .

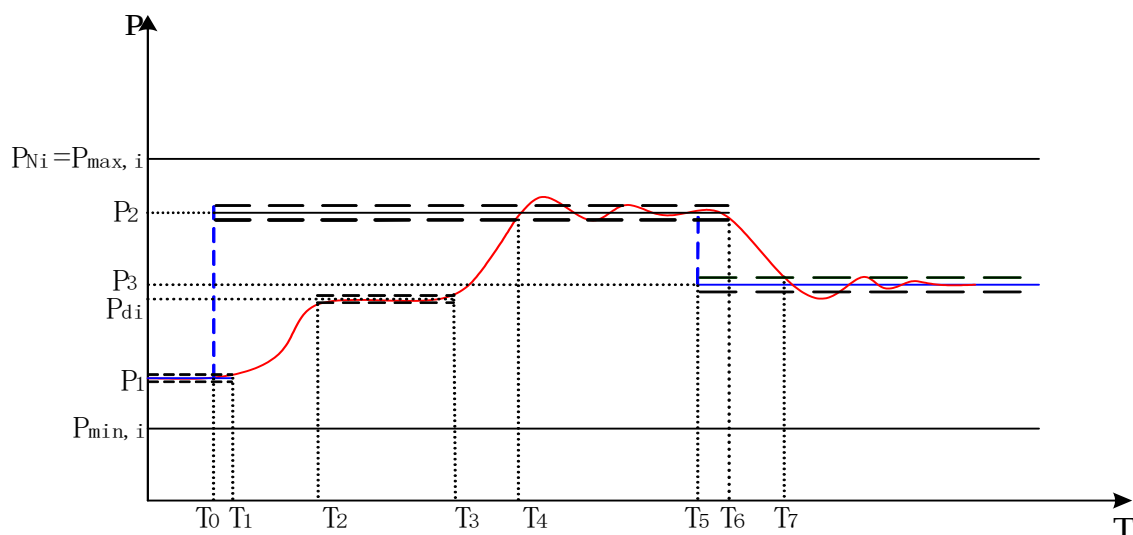


Figure 1. The standard AGC response.

The time period from T_2 to T_3 is for the start-up time duration for one additional coal mill to provide the required coal powders. By the time instant T_4 , the unit output reaches and stays at the steady-state value P_2 until the time instant T_5 . Afterwards, the unit receives a new AGC command to reduce its output to P_3 , and the unit begins to reduce its output at the time instant T_6 and reach the desired steady-state value around P_3 at the time instant T_7 . Three AGC performance indices have been defined, namely, the regulation speed, adjustment accuracy and response time, denoted respectively by K_1 , K_2 and K_3 . These mathematical definitions and computing methods of these performance indices are introduced in the following three subsections.

Based on the above AGC response, three performance indices have been defined, namely, the regulation speed, adjustment accuracy and response time, denoted respectively by K_1 , K_2 and K_3 . The mathematical definitions and computing methods for these performance indices are introduced in the following three subsections.

2.1. Regulation speed

Regulation speed is defined as the speed of power generation unit making response to the AGC command. For one specific power unit i , its regulation speed in the j -th AGC command response is defined as follows. The power generation unit increases its actual power output, corresponding to the time period $T_1 \sim T_4$ in Figure 1. This time period includes a special time period that the coal mill starts, so that the effect caused by starting coal mill should be eliminated in the calculation of regulation speeds. In the stage of the power generation unit reducing its actual power output, corresponding to the time period $T_5 \sim T_6$ in Figure 1, the coal mill does not stop, so that it is not necessary to consider the effect of stopping coal mills. Taking both two time periods into consideration, the regulation speed can be calculated as

$$v_{i,j} = \begin{cases} \frac{P_{Ei,j} - P_{Si,j}}{T_{Ei,j} - T_{Si,j}} & P_{di,j} \notin (P_{Ei,j}, P_{Si,j}) \\ \frac{P_{Ei,j} - P_{Si,j}}{T_{Ei,j} - T_{Si,j} - T_{di,j}} & P_{di,j} \in (P_{Ei,j}, P_{Si,j}) \end{cases} \quad (1)$$

Here $v_{i,j}$ denotes the regulation speed power unit i of in the j -th adjustment, $P_{Ei,j}$ denotes the power unit output at the end of the regulation process, $P_{Si,j}$ is the power unit output at the beginning of the regulation process, $T_{Ei,j}$ denotes the end time of the regulation process, $T_{Si,j}$ denotes the start time of the regulation process, $P_{di,j}$ denotes the power unit output when the coal mill starts or stops, $T_{di,j}$ is the power unit consuming time for starting or stopping coal mills. The performance index on the regulation speed is obtained as

$$K_1^{i,j} = 2 - \frac{v_{N,i}}{v_{i,j}} \quad (2)$$

Here $v_{N,i}$ denotes the standard regulating speed of the power generation unit i . The value of $v_{N,i}$ depends on the types of power generation units. For example, the value of $v_{N,i}$ is 1.5% of the rated power for a thermal power unit with a drum boiler and a direct-blowing pulverizing system. Thus, the value of $v_{N,i}$ should be determined carefully in practice. $K_1^{i,j}$ denotes the performance of the unit i 's adjustment rate compared with its standard regulating speed in its j -th actual adjustment. If the value of $K_1^{i,j}$ is less than 0.1, then $K_1^{i,j}$ is set to 0.1.

2.2. Adjustment accuracy

Adjustment accuracy is the difference between the actual generated power and the AGC command when the AGC response completes. The computing process of adjustment accuracy can be described as follows: If a thermal power unit does not receive an AGC command, it will run in a stable operation stage as shown in the time period $T_4 \sim T_5$ in Figure 1. In this time period, the mean of the integrating absolute error between the actual generated power and the AGC command is calculated as

$$\Delta P_{i,j} = \frac{\int_{T_{Si,j}}^{T_{Ei,j}} |P_{i,j}(t) - P_{i,j}| \times dt}{T_{Ei,j} - T_{Si,j}} \quad (3)$$

Here $\Delta P_{i,j}$ denotes the control deviation of a power generation unit i with the j -th adjustment. $P_{i,j}(t)$ and $P_{i,j}$ are the actual generated power and the AGC command value during this time period, respectively. $T_{Ei,j}$ and $T_{Si,j}$ are the starting and ending time instants of this time period, respectively. The performance index on the adjustment accuracy is computed as

$$K_2^{i,j} = 2 - \frac{\Delta P_{i,j}}{\text{Adjust allowable deviation}}. \quad (4)$$

The parameter of allowable adjust deviation is 1 % of the rated power of a power generation unit in practice. $K_2^{i,j}$ is a measurement of actual regulation deviation on the condition of taking the allowable deviation into consideration. If the computing result of $K_2^{i,j}$ is less than 0.1, then $K_2^{i,j}$ is set to 0.1.

2.3. Response time

Response time refers to the time between a power generation unit receiving an AGC command and starting the response. According to the changing directions of the generated power, there are two response times, denoted by $t_{i,j}^{up}$ and $t_{i,j}^{down}$,

$$t_{i,j}^{up} = T_1 - T_0, \quad t_{i,j}^{down} = T_6 - T_5 \quad (5)$$

The performance index on the response time is calculated as

$$K_3^{i,j} = 2 - \frac{t_{i,j}}{\text{standard response time}}. \quad (6)$$

Here $t_{i,j}$ is response time of a power generation unit i consuming time to executive the j -th adjustment. In general, the requirement of the AGC response time should be less than 20 seconds. Thus, the value of $t_{i,j}$ should be less than 20 seconds. $K_3^{i,j}$ is a measurement of actual response time on the condition of taking the standard response time into consideration. If the value of $K_3^{i,j}$ is less than 0.1, then $K_3^{i,j}$ is set to 0.1.

3. A new method to estimate and predict AGC performance indices

3.1. Dynamic models

The input and output model for a discrete-time dynamic time-invariant dynamic system can be represented in the form of difference equation [9-11],

$$y(k) + a_1 y(k-1) + \dots + a_n y(k-n) = b_1 u(k-1) + \dots + b_n u(k-n). \quad (7)$$

By Z-transform for the difference equation with zero initial conditions, the model can be rewritten as

$$G(z) = \frac{Z\{y(k)\}}{Z\{u(k)\}} = \frac{b_1 z^{-1} + b_2 z^{-2} + \dots + b_n z^{-n}}{1 + a_1 z^{-1} + \dots + a_n z^{-n}}. \quad (8)$$

Here z is a shift operator,

$$z^{-1} y(k) = y(k-1), \quad (9)$$

and its relationship with the Laplace operator s is

$$z^{-1} = e^{-Ts}, \quad (10)$$

where T is the sampling period. For a concise expression, the equation (8) can be rewritten as

$$A(z^{-1})y(k) = z^{-d} B(z^{-1})u(k) \quad (11)$$

$$\begin{aligned} A(z^{-1}) &= 1 + a_1 z^{-1} + a_2 z^{-2} + \dots + a_{na} z^{-na} \\ B(z^{-1}) &= b_1 z^{-1} + b_2 z^{-2} + \dots + b_{nb} z^{-nb} \end{aligned} \quad (12)$$

Here na, nb and d are structural parameters, and a_i, b_j 's are the model parameters. If the effect of disturbances or measurement noises is taken into consideration, then a noisy term should be included,

$$A(z^{-1})y(k) = z^{-d}B(z^{-1})u(k) + D(z^{-1})e(k) \quad (13)$$

$$D(z^{-1}) = 1 + d_1z^{-1} + d_2z^{-2} + \dots + d_{nd}z^{-nd} \quad (14)$$

Here $D(z^{-1}) = 1 + d_1z^{-1} + d_2z^{-2} + \dots + d_{nd}z^{-nd}$. Because the thermal power unit is a first-order continuous-time dynamic system [12-13], the discrete-time model should be transformed into a first-order continuous-time model,

$$G(s) = \frac{K_P}{1+T_{P1}s} \cdot e^{-T_d s} \quad (15)$$

The parameters of this continuous-time model are used to calculate the AGC performance indices.

3.2. Estimation and prediction of AGC performance indices

3.2.1. Regulation speed

The regulation speed is defined to measure the time duration required by a power generation unit to complete an AGC response. The input and output for the continuous-time model in (15) are the AGC command and the actual generated power. The steady-state response time of the model is equal to $4 \cdot T_{p1}$.

Thus, the regulation speed is obtained as

$$K_1 = 4 \cdot T_{p1}. \quad (16)$$

The computing method of the regulation speed described in Section 2.1 for the same power generation unit will yield different estimation results when two inputs are all step signals with different amplitudes. This is illustrated by a numerical example. Suppose the continuous-time model of the power generation unit is $G(s) = 2/(3s+1)e^{-2s}$. If the input is a unit step signal, then the regulation speed of this system is $(2-0)/(20-0) = 0.1$. If the step is with the amplitude 2, then the system response is also 2 times of the unit step response. As a result, the regulation speed becomes 0.2. However, the system is not changed at all. This controversial fact is shown in Figure 2. Thus, the current method of calculating the regulation speed K_1 will lead to erroneous results.

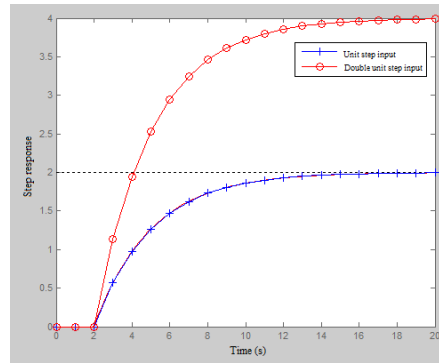


Figure 2. Step responses of different step inputs.

3.2.2. Adjustment accuracy

Adjustment accuracy refers to the deviation of the actual generated power from the AGC command. The steady-state gain of the continuous-time model in (15) is the ratio between changes in the AGC command with respect to the changes of the actual generated power. Thus, the performance index on the adjustment accuracy can be calculated from the steady-state gain as

$$K_2 = 1 - K_p. \quad (17)$$

The computing method of the adjustment accuracy described in Section 2.2 is to compute the average of absolute values of cumulative errors in steady state. This method is based only on a few

steady-state data points and do not take all actual power output values in the response into consideration. Thus, this method is severely affected by random disturbances or measurement noises.

3.2.3. Response time

Response time refers to a time duration that the power generation unit needs to change its output from the current value to pass through regulation dead band after receiving an AGC command. The delay time of the continuous-time model in (15) can indicate the response time of the power generation unit responding to its AGC command. Hence, the system delay time is indeed the response time [14],

$$K_3 = T_d. \quad (18)$$

By contrast, the computing method of the response time described in Section 2.3 often leads to inaccurate estimate in practice. This is due to a fact that the response time is obtained by reading some special data points, and would be severely affected by the presence of random disturbances or measurement noises.

3.2.4. A polynomial model for prediction

The AGC performance indices are usually different for various operating conditions of generated actual powers. A nonlinear model can be established to describe the relationship between the above calculated performance indices and the AGC command. In particular, a third-order polynomial model is adopted by taking the AGC command as the independent variable x and one performance index K_1, K_2 or K_3 as the dependent variable y ,

$$y(x) = p_1 x^3 + p_2 x^2 + p_3 x + p_4 \quad (19)$$

The values of p_1, p_2, p_3 and p_4 can be estimated via the standard linear least-squares method to make a curve fitting between the AGC command and K_1, K_2 or K_3 , respectively. The performance indices K_1, K_2 and K_3 can be predicted for the current value of the AGC command based on the polynomial model.

4. Industrial case studies

This section provides industrial case studies on real-time data points from a large-scale thermal power plant in North China Power Grid, in order to verify the effectiveness of the proposed method. The continuous-time model (15) is identified for different AGC commands. The performance indices K_1, K_2 and K_3 are calculated according to the equations (16), (17) and (18), respectively. Figure 3 presents a typical AGC response. The sampling period is 1 second. The identified continuous-time model in (15) is

$$G(s) = \frac{K_p}{1 + T_{p1} \cdot s} \cdot e^{-T_d \cdot s} = \frac{0.8964}{1 + 66.66 \cdot s} \cdot e^{-1 \cdot s}$$

Thus, the estimated performance indices are

$$K_1 = 4 \cdot T_{p1} = 266.64, K_2 = 1 - K_p = 0.1036, K_3 = T_d = 1$$

The AGC performance indices are calculated for a set of AGC command values in the vector

$$SP = [53, 56, 59, 62, 65, 68, 71, 73, 75, 77, 79, 81, 83, 84, 84] \quad (20)$$

The AGC command data segment will be selected if it is within the range of $SP[i] \pm 1, i = 1, 2, \dots, 15$, and lasts no less than 10 minutes. The actual power data are selected according to the corresponding AGC command time periods. Thus, 15 groups of K_1, K_2 and K_3 can be obtained. Three polynomial models are estimated by taking the AGC command values as the samples of the independent variable and the performance indices $K_1[i], K_2[i], K_3[i], i = 1, 2, \dots, 15$ as the samples of the dependent variable.

The estimated values of p_1 , p_2 , p_3 and p_4 are listed in Table 1. The fitting curves are plotted in Figure 4.

Based on the fitting curves between K_1 , K_2 , K_3 and AGC command values, the values of K_1 , K_2 , K_3 can be predicted. The effectiveness of this method can be verified by the absolute errors between prediction values and the actual values of K_1 , K_2 and K_3 . The absolute errors are shown in Table 2, for three AGC command values 63%, 74% and 81%. As shown in Table 2, when the AGC command value is less than 75%, the estimation of the regulation speed K_1 , adjustment accuracy K_2 and response time K_3 is accurate. However, if the AGC command value is more than 75%, the predictive values are a little bit far from their actual values. This phenomenon is caused by the fact that there are few data samples for the fitted curves when the AGC command value is more than 75%. Thus, more data samples need to be collected to improve the prediction accuracies.

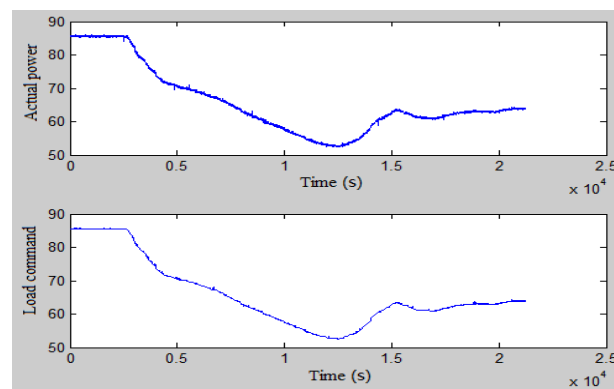


Figure 3. The actual power and AGC command data

Table 1. The curve fitting results of p_1 , p_2 , p_3 and p_4

	p_1	p_2	p_3	p_4
K_1	0.0019	-0.282	10.4201	33.1565
K_2	-9.7781×10^{-5}	0.0182	-1.1028	22.8352
K_3	-3.0729×10^{-4}	0.0591	-3.6715	76.9072

Table 2. The absolute errors between predictive values of K_1 , K_2 , K_3 and their actual values for different AGC command values.

Performance index	AGC command 63%	AGC command 74%	AGC command 81%
K_1	0.1869	0.1303	1.9630
K_2	0.0300	0.2059	0.4367
K_3	0.0725	0.0445	0.2707

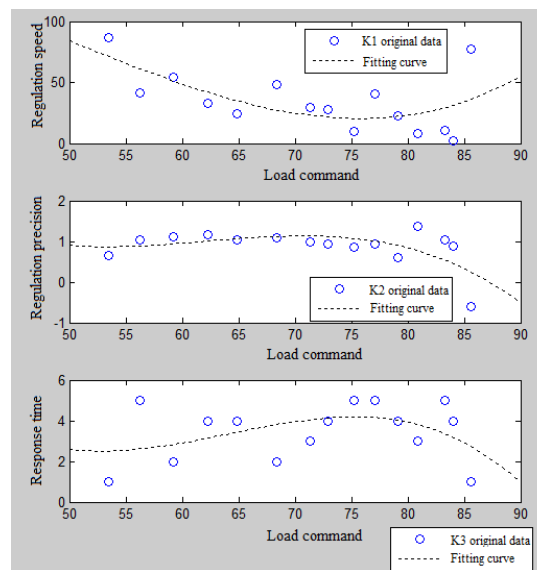


Figure 4. The fitting curves between K_1 , K_2 , K_3 and AGC command values.

5. Conclusion

The paper proposed a new method to estimate and predict the AGC performance indices for power generation units. The system identification technique was used to estimate a continuous-time dynamic model describing the AGC response. Nonlinear polynomial models were built to describe relationships between the AGC performance indices and the AGC command values. The effectiveness of the proposed method was illustrated via industrial case studies.

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