Estimation of Hydro Turbine-Governor System's Transfer Function from PMU Measurements

Dinh Thuc Duong and Kjetil Uhlen
Department of Electric Power Engineering
Norwegian University of Science and Technology
Trondheim, Norway

Erik Alexander Jansson
Statnett
Oslo, Norway

***Abstract*—Generation in the Nordic power system is dominated by large number of hydro power plants, especially in Norway and Sweden. There are indications that, during the last decade, the frequency quality in the system has deteriorated; the number of minutes when the frequency stays outside the permissible range has been increasing. There is ongoing work to find the root of the problem and solutions to improve the quality of frequency. Among other measures, it is important to know the actual dynamic characteristics of the turbine-governor response of power plants. Regarding this issue, the paper presents the work on using state-of-the-art system identification methods to estimate the transfer function of the turbine-governor systems with ambient data. With only PMU measurements at the high voltage side of generator transformers, the identification methods work properly and provide satisfactory estimation.**

***Index Terms*— ARX, Governor, PMU, SRIVC, Turbine.**

I. Introduction

Frequency is one of the key parameters of power systems; it is an indicator for instantaneous balance of active power between generation and load. Primary frequency control is a distributed process, but the overall responsibility for maintaining power balance and system frequency lies with the Transmission System Operators (TSOs). In the Nordic power system, the permissible frequency range is 50±0.1 Hz [1]. Recent concern about deterioration of frequency quality can be illustrated by the 4-minute trend curve of system frequency shown in Fig. 1. Here, there are two noticeable features: the occasional drop of frequency below the permissible lower limit (49.9Hz), and the slow variations of the frequency, typically with periods between 40 to 90 seconds. This has raised concerns in recent years. On the transmission system operator's side, there is a need to know or be able to verify the provision of frequency controlled reserves (FCR) by generators. Traditionally, this was equivalent to knowing the steady state frequency droop settings of the power plants' turbine governors. However, the power systems are never in a steady state condition. With increasing penetration of renewable sources, operation condition can change quickly. Thus, in addition to the steady state response of the turbine-governors (the droop), it is important to know the main dynamic properties, such as the bandwidth that can be captured if the transfer function of the turbine governing system is known.

In control engineering, the system identification field has been highly developed. Several works have been done and well presented in the literature [2]-[7]. With this tool, it is possible to identify the transfer function of a system based on measurements of its input and output. This pays the way for estimating the model of the turbine-governor system of generators. Nowadays, phasor measurement units (PMUs) are widely deployed in power systems. This instrument provides synchronous measurements of frequency, current and voltage, which are input data required by the identification process.

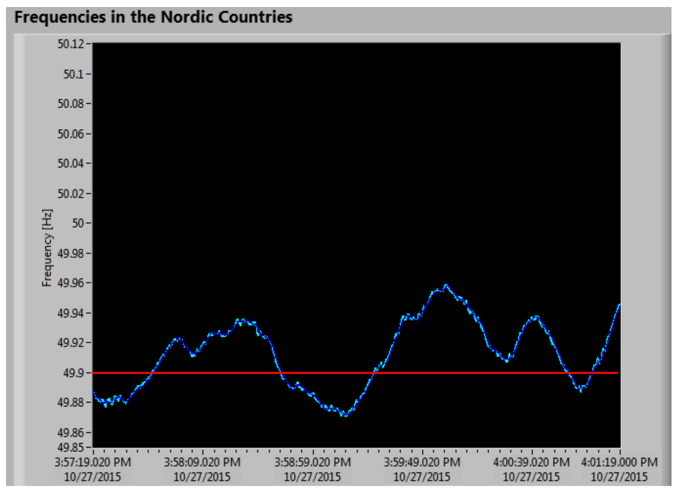

Figure 1. A snapshot of the frequency in the Nordic power system.

The paper is structured as follows. First, the basics of system identification are presented in Section II. Then, the proposed technique to estimate the turbine-governor system based on PMU measurements is presented in Section III. The paper continues with Section IV, where the results are presented. Finally, conclusion is drawn in Section V.

II. Basics of System Identification

A. *The ARX model [7]*

Consider a single input single output (SISO) and noise-free system, where $u(k)$ and $y(k)$ are the discrete-time input and

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output, respectively. The linear ARX model is formulated by a difference equation as

$$\begin{aligned} & y(k+n)+a_1 y(k+n-1)+\cdots+a_n y(k) \\ & \quad = b_0 u(k+m)+b_1 u(k+m-1)+\cdots+b_m u(k) \end{aligned} \tag{1}$$

or in the compact form

$$A(q)y(k)=B(q)u(k) \tag{2}$$

where

- $A(q)=q^n+a_1q^{n-1}+\cdots+a_n$
- $B(q)=b_0q^m+b_1q^{m-1}\cdots+b_m$
- $a_1, \ldots, a_n, b_1, \ldots, b_m$ are coefficients,
- n and m are the order of $A(q)$ and $B(q)$, respectively, ($n \geq m$)
- q is forward-shift operator, i.e. $q^n u(k)=u(k+n)$.

The transfer function in the z-domain of the model described by (1) is

$$H(z)=\frac{b_0z^m+b_1z^{m-1}+\cdots+b_m}{z^n+a_1z^{n-1}+\cdots+a_n} \tag{3}$$

Let us assume that N measurements of the input and output have been taken, given that $u(k) = [u(1), u(2), \ldots, u(N)]$ and $y(k) = [y(1), y(2), \ldots, y(N)]$. Based on (1), one can establish the following set of equations:

$$\begin{aligned} & y(1+n)+a_1y(n)+\cdots+a_ny(1)=b_0u(1+m)+b_1u(m)+\cdots+b_mu(1) \\ & y(2+n)+a_1y(1+n)+\cdots+a_ny(2)=b_0u(2+m)+b_1u(1+m)+ \\ & \qquad\qquad \cdots+b_mu(2) \\ & \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ & y(N)+a_1y(N-1)+\cdots+a_ny(N-n) \\ & \quad =b_0u(N-n+m)+b_1u(N-n+m-1)+\cdots+b_mu(N-n) \end{aligned} \tag{4}$$

Define

$$\theta=\left[a_1,\ \ a_2,\cdots,a_n,\ \ b_1,\ \ b_2,\cdots,b_m\right]^T,$$

$$y=\left[y(1+n)\quad y(2+n)\cdots y(N)\right]^T,$$

$$\phi=\begin{bmatrix} -y(n) & \cdots & -y(1) & -u(1+m) & \cdots & u(1) \\ -y(n+1) & \cdots & -y(2) & -u(2+m) & \cdots & u(2) \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ -y(N-1) & \cdots & -y(N-n) & -u(N-n+m) & \cdots & -u(N-n) \end{bmatrix}$$

Equation (4) can be rewritten as

$$y=\phi\theta \tag{5}$$

It is noted that (5) is an overdetermined set of equations, where θ is the unknown, which can be estimated by using the least squares method:

$$\theta=\left(\phi^T\phi\right)^{-1}\phi^T y \tag{6}$$

After all the coefficients are identified, the analysis of frequency response of $H(z)$ is easily carried out.

B. The simplified refined instrumental variable method (SRIVC)[4]- [5]

Consider a linear, continuous, time-invariant and noise-free SISO system. The relation between the input and output can be described by a differential equation as

$$\begin{aligned} & y^{(n)}(t)+a_1y^{(n-1)}(t)+\cdots+a_nx^{(0)}(t)= \\ & b_0u^{(m)}(t)+b_1u^{(m-1)}(t)+\cdots+b_mu^{(0)}(t) \end{aligned} \tag{7}$$

where $y^{(i)}(t)$ denotes the i^{th} derivative of the $y(t)$ with respect to time, and $n \geq m$. Equation (7) can be rewritten in the compact form as

$$A(p)y(t)=B(p)u(t) \tag{8}$$

with

$$A(p)=p^n+a_1p^{n-1}+\cdots+a_n$$

$$B(p)=b_0p^m+b_1p^{m-1}+\cdots+b_m$$

where p is differential operator, i.e. $p^i x(t)=\frac{d^i x(t)}{dt^i}$. Based on this model, the transfer function of the system in the s-domain is

$$G(s)=\frac{b_0s^m+b_1s^{m-1}+\cdots b_m}{s^n+a_1s^{n-1}+\cdots a_n} \tag{9}$$

Let us introduce a filter function

$$F(p)=\frac{1}{A(p)} \tag{10}$$

Applying the filter $F(p)$ on both sides of (8) and neglecting transient initial effects yield

$$A(p)F(p)y(t)=B(p)F(p)u(t) \tag{11}$$

Define a set of filters $F_i(p)$ for $i=0,1,\cdots,n$ as

$$F_i(p)=\frac{p^i}{A(p)} \tag{12}$$

Now, (11) can be expressed as:

$$\begin{aligned} & \{F_n(p)+a_1F_{n-1}(p)+\ldots+a_nF_0(p)\}x(t) \\ & =\{b_0F_m(p)+\ldots+b_mF_0(p)\}u(t) \end{aligned} \tag{13}$$

In time domain, denoting $f_i(t)$ as the set of corresponding functions of $F_i(p)$, (13) becomes

$$y_f^{(n)}(t)+a_1y_f^{n-1}(t)+\ldots+a_ny_f^0(t)=b_0u_f^m(t)+\ldots+b_mu_f^{(0)} \tag{14}$$

where

$$y_f^{(i)}(t)=f_i(t)*y(t)$$

$$u_f^{(i)}(t)=f_i(t)*u(t)$$

with * is the convolution operator.

At particular instant of time $t=t_k$, rearranging (14) leads to the linear aggressive model in the form of

$$y_f^{(n)}(t_k)=\phi_f^T(t_k)\theta \tag{15}$$

where

$$\theta=\left[a_1,\ \ a_2,\cdots,a_n,\ \ b_0,\ \ b_1,\cdots,b_m\right]^T \tag{16}$$

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$$\phi_f^T(t_k) = [-y_f^{(n-1)}(t_k), -y_f^{n-2}(t_k), \cdots, -y_f^{(0)}(t_k), u_f^{(m)}(t_k), \\ u_f^{(m-1)}(t_k), \cdots, u_f^{(0)}(t_k)] \tag{17}$$

Given N measurements of the input and output taken at time instants $t_1, t_2, \ldots, t_N$, one can form an overdetermined set of equations from (15), which gives the estimation of the unknown as [5]:

$$\hat{\theta}_N^{LS} = \left[\sum_{k=1}^{N} \phi_f(t_k)\phi_f^T(t_k)\right]^{-1} \sum_{k=1}^{N} \phi_f(t_k) y_f^{(n)}(t_k) \tag{18}$$

Although the coefficients have been estimated, the result is unsatisfactory if the system is disturbed by colored noise [5]. To solve this problem, one can use the instrumental variable (VI) method. Let the output be estimated by

$$\hat{y}(t_k) = \frac{B(p, \hat{\theta}_N^{LS})}{A(p, \hat{\theta}_N^{LS})} u(t_k) \tag{19}$$

and then compute the instrumental variables as

$$\hat{y}_f(t_k) = F(p)\hat{y}(t_k) \tag{20}$$

Now, the VI vector can be formulated by

$$\hat{\phi}_f^T(t_k) = [-\hat{y}_f^{(n-1)}(t_k), -\hat{y}_f^{n-2}(t_k), \cdots, -\hat{y}_f^{(0)}(t_k), u_f^{(m)}(t_k), \\ u_f^{(m-1)}(t_k), \cdots, u_f^{(0)}(t_k)] \tag{21}$$

This gives solution for the identification problem:

$$\hat{\theta}_N^{VI} = \left[\sum_{k=1}^{N} \hat{\phi}_f(t_k)\phi_f^T(t_k)\right]^{-1} \sum_{k=1}^{N} \hat{\phi}_f(t_k) y_f^{(n)}(t_k) \tag{22}$$

The SRIVC method is an iterative process, in which the vector $\hat{\theta}_N^{VI}$ at the previous step is used to compute the instrumental variables, which are used to update the value of $\hat{\theta}_N^{VI}$ in the current step. The process continues until it converges. Details of the method are presented in [4].

III. ESTIMATION OF TRANSFER FUNCTION OF THE TURBINE-GOVERNOR SYSTEM FROM PMU MEASUREMENTS

Consider a power plant that is in operation and synchronized to the grid. The closed loop speed/frequency control system can be depicted as in Fig. 2, where *our goal is to identify the transfer function $H_1(j\omega)$*, representing the turbine-governor system, including penstock and gate dynamics. To achieve this goal, two main assumptions must be made:

First, the synchronously interconnected power system must be very large compared to the monitored plant so that the variation in active power ΔP_e of one generator does not significantly influence the grid frequency. Hence, $H_3(j\omega)$ is approximately zero and can be neglected.

Second, we focus on the slower dynamics, only (i.e. below approximately 0.1 Hz), meaning that we neglect the electromagnetic and electromechanical dynamics associated with the generator. Thus, at frequencies below approximately 0.1-0.2 Hz, it is reasonable to assume that the mechanical power of the turbine is equal to the electrical power measured at the terminal of the synchronous machine, i.e. $H_2(j\omega) = 1$. With these assumptions, the open loop transfer function $H_1(j\omega)$ *for* $\omega < 0.1$ *Hz* can be identified using the following measurements:

- time series of measured frequency as input: $\Delta f(t)$.
- time series of generator active power as output:

$$\Delta P_e = P_{measured} - P_{ref}$$

where P_{ref} is the setpoint of active power.

It is noted that the identification methods consider $H_1(j\omega)$ as a black box and use measurements of the input Δf and output ΔP_e to estimate this system. Thus, performance of the estimation methods is not affected by dynamic response of any element of the estimated system $H_1(j\omega)$, including the gate dynamics.

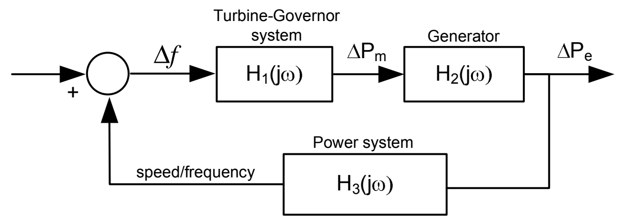

Figure 2. Model of the turbine-governor system of a power plant.

The estimation process includes the following steps:

1. **<u>Step 1: Data preparation</u>**

- Measure the grid frequency and active power of the generator continuously over a period of time, which should be long enough to capture slow response of the turbine-governor system. During this period, there must not be any adjustment of the setpoint P_{ref} so that variation of the active power is purely driven by the frequency of the grid. The measurements should be synchronized to reflect the actual response of the system. Thus, measurements from PMUs are satisfactory.
- Compute the input and output. In many cases, the setpoint P_{ref} is unknown. However, this parameter can be identified by the trial-and-error method. Initially, P_{ref} can be roughly estimated based on the measured active power and the frequency. After that the transfer function system can be identified. After this step, one can simulate the output based on the input and the recently estimated model. By comparing the measured and simulated power output, one can gradually adjust the value of P_{ref} until it matches the actual setpoint.
- It is noted that in order to have the system properly estimated by the ARX and SRIVC methods, the mean of each signal (input and output) should be removed.

2. **<u>Step 2: Model selection</u>**

- For the ARX model, the basic setting parameters are the orders n and m. If the orders are low, the model cannot capture the dynamic response of the system; consequently, the estimated transfer function is not accurate. However, very high order does not give good estimation, either. One can start with low order (e.g. n = 10, m = 10), and then increase it until the estimation is satisfactory.
- In the SRIVC method, the number of poles and zeros (parameters n and m in (8)) is the setting parameters.

Similar to the case of the ARX model, both low and high orders do not give proper estimation. Initially, one can start with the models of the considered system, which are widely known in the literature, e.g. [11].

3. **Step 3: Estimation of the transfer function**

- In Matlab, all the identification methods presented in the previous section are available in the System Identification Toolbox. One can also use the command *arx* to estimate the transfer function based on the ARX model and the *tfest* command to use the SRIVC model. Detailed information is presented in [8], [9].
- In addition, one can also estimate the continuous transfer function with the other two toolboxes: CONTSID and CAPTAIN [4], [10].

4. **Step 4: Model validation**

- After the model has been identified, it should be validated. First, the input obtained from measurements is used to excite the estimated model to produce the simulated output. Then, this output is compared to the measured active power. In Matlab, this task can be done by using the command *compare*. To evaluate how well the model is estimated, the fit criterion is defined as [3]

$$Fit = 100\left(1 - \frac{norm(\hat{y}(t) - y(t))}{norm(y(t) - mean(y(t))}\right) \quad (23)$$

where $\hat{y}(t)$ and $y(t)$ are the simulated and measured outputs, respectively.

- System identification is an iterative process. The fit of low-order model is normally poor. As the order increases, the fit becomes better and better until the system is best estimated, where the identification process should be terminated. Higher orders do not result in better estimation, but worse.

IV. RESULTS

To examine the performance of the identification tools, the first test case is conducted with use of operational data of a generator, called G1, at a hydro power plant in Norway. The generator is connected to the transmission system and has active power about 70MW as shown in Fig. 3. Measurements of the grid frequency and the active power are obtained from a PMU with the reporting frequency is 50 samples per second. The time window used is 2000s. During this period, the frequency is within the limit and there is no large disturbance in the grid. In addition, a low-pass filter IIR is used to suppress noise and high frequency dynamics. The estimation is conducted based on the ARX and SRIVC models in the System Identification Toolbox in Matlab. The order of the ARX model is n = 15, m = 15. For the SRIVC model, n = 8 and m = 4. These parameters are also used in all other test cases presented in this paper.

Fig. 4 shows the Bode plot of the two estimated models and the HYGOV model in [12]. Setting parameters of the HYGOV model are the following: $R = 0.052$, $r = 0.4$, $T_r = 8.0$, $T_f = 0.05$; $T_g = 0.2$, $T_w = 1.2$, $A_t = 1.0$, $D_{turb} = 0$ and $q_{NL} = 0$. As can be seen, the two estimated models have comparable gain and phase angle. Compared to the HYGOV, the estimated models are very similar but they have higher bandwidth. To validate the results, the measured frequency is used to excite the three models and then the simulated outputs are compared with the actual measured active power as shown in Fig. 5. As can be seen, the estimated outputs are very close to the output of the real system; the fit of the estimated models is 93.84% (ARX method) and 93.77% (SRIVC method); meanwhile, the HYGOV model has the fit of 88.09%.

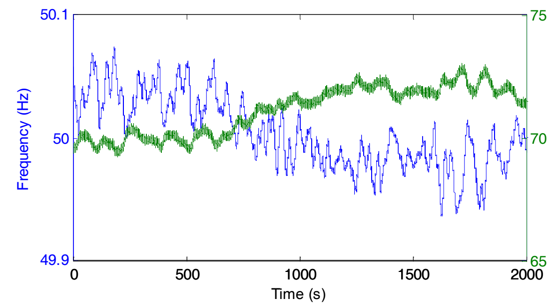

Figure 3. Grid frequency and active power of G1 in test case 1.

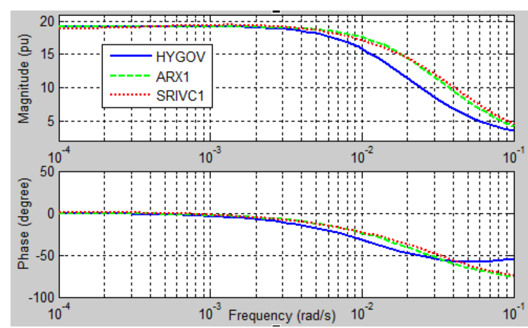

Figure 4. Bode plot of the estimated models in test case 1 and HYGOV.

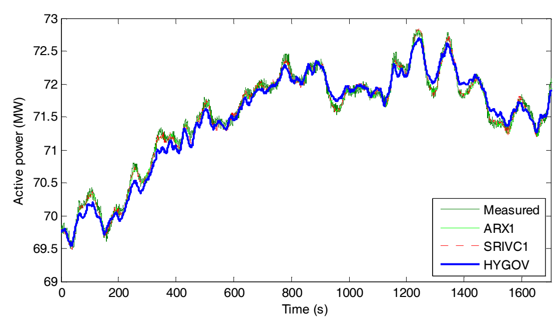

Figure 5. Estimated and measured active power of G1 in test case 1.

The second test uses another time series data of G1, which is collected when there is a significant system disturbance (loss of load). This event is observed by a sharp increase of frequency at $t = 1400$s in Fig. 6. Correspondingly, the active power quickly drops from 68MW to about 65MW. To examine the consistency of the identification tools, the frequency response obtained from this observation period (ARX2 and SRIVC2) is compared with the response of the previous estimated models (ARX1 and SRIVC1) in Fig. 7. As can be seen, there is small mismatch of the gain among the models. Considering the phase angle, there is almost no difference at low frequency. However, the mismatch becomes slightly larger when the frequency is in the range of 0.007 – 0.1 rad/s. Nonetheless, both approaches work properly in both normal and disturbance conditions.

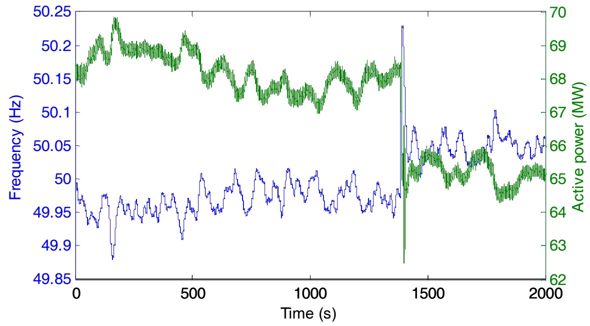

Figure 6. Grid frequency and active power of G1 during disturbance.

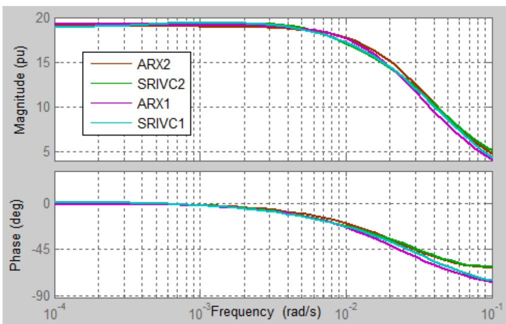

Figure 7. Bode plot of estimated models obtained from two different observation periods.

In the Nordic power system, droop setting of governors is sometimes adjusted as part of an ancillary service to provide frequency containment reserves (FCR). Fig. 8 shows the Bode plot of the two transfer functions estimated from two different observation periods at another generator, called G2. As can be seen, the steady state gain of the transfer function has changed from 21 pu to 16.66 pu, meanwhile the phase angle remains unchanged at low frequency. Obviously, the identification method can track the changes of the turbine-governor system fairly well. Whether the difference in this case is due to change in droop setting or due to other reasons, such as non-linearities in the turbine characteristic, is not known.

In addition to the above test cases using the data of the generators G1 and G2, several turbine-governor systems of other generators in the Norwegian power system are also estimated. The summary of the results is presented in Table 1. In general, the ARX model has better performance than the SRIVC in all the test cases.

V. Conclusion and Discussion

The paper has presented the work on using system identification tools to estimate the transfer function of some hydro turbine-governor systems in Norway. It has been seen that the tools are able to identify properly the transfer function with data collected in normal operation as well as during disturbance. The fit of the identified model is satisfactory, and the estimated outputs of the model are very close to the actual active power of the tested generators. Although the ARX is a simple model, it gives better performance than the SRIVC model with respect to the fit of the model and computing time.

The main motivation behind this work is to explore the possibility of (nearly) online monitoring of frequency containment reserves. If successful, this is a candidate application for the future Wide Area Monitoring Systems.

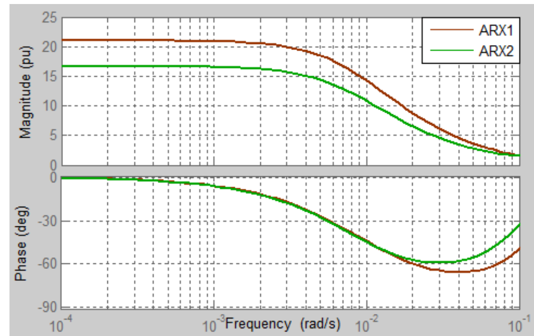

Figure 8. Bode plot of the same system but with the different droops.

TABLE I. SUMMARY OF SYSTEM IDENTIFICATION RESULTS

Generator	ARX		SRIVC	
	Fit (%)	*Computing time (s)*	*Fit (%)*	*Computing time (s)*
G1	93.84	3.04008	93.77	190.8204
G2	83.32	3.5412	70.87	136.8597
G3	87.86	3.9	82.45	132.9597
G4	86.95	4.8984	69.4	178.7771
G5	82.36	3.666	75.62	137.8113
G6	78.32	3.588	76.1	136.7661

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