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# ON PID CONTROLLER DESIGN FOR A HIGH-ORDER SYSTEMS

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**Abstract:** Investigation of PID (proportional-integral-derivative) controller and its shorter variants (PI and P) for high-order systems has been carried out and presented in this paper. Famous Ziegler-Nichols method based on frequency response was used without previous model reduction of system. Tuning procedure and system functioning were performed by means simulations. According specificity in the obtained results, caused by system particularities, some corrections in the PID parameters tuning rules have been suggested. Applicability of proposed procedure has been proved on the several high-order systems.

**Key words:** PID control, high-order systems, non-reduced models

## INTRODUCTION

Appropriate mathematical model of system is very important precondition for its successful control. It is usually necessary to make a compromise between order of mathematical model and amount of information that are enough for representation of system dynamic behavior. High-order model of system can be obtained both using various identification procedures and by means physical laws. These high-order models make troubles, because computational methods for tuning of PID controller have been usually derived up to second-order models. Many approaches tend to overcome this obstacle. In this regard, Desai and Prasad [1] developed method for model reduction of linear system. This method is consisted of big bang big crunch optimization technique and stability equation method for numerator and denominator terms of reduced system, respectively. Isaksson and Graebe [2] researched the other one approach to model reduction intended for PID design. Safonov and Chiang [3] tried to achieve robust control, where they used model reduction, too. Wide and comprehensive overview to model reduction problem, in order to make model of system easier for controller tuning, has been given by Obinata and Anderson [4]. A new model reduction method, dealing with fractional order plus time delay model, for PID controller design has been developed in [5]. Suitable new method for model reduction using genetic algorithm with accuracy checking in the Nyquist plane, as wel as tuning rule for fractional PID controller, have been investigated and determined in the [6]. Beside aforementioned attempts to reduce the system to acceptable form for controller design, there are another set of approaches that contain tuning rules without changing system mathematical model. Fractional order PID controller enables more possibilities regarding fulfilling demands for system properties. So, it is fully comprehensible the presence of numerous attempts for its design. In this regard, one of them Shah and Agashe [7] developed fractional order PID controller for high order system based on optimal tuning in time-domain without model reduction.

This investigation has also aim to design PID controller without previous system model reduction. It has been carried out by using and afterward correcting Ziegler-Nichols method based on frequency response [8], which is clearly explained in [9].

Paper is consisted of five sections. This introduction is followed by section containing problem definition. Hydrostatic power transmitter as controlled object, PID controller design for it and its variation and suggested corrections of the expressions for controller terms calculations are involved in the section titled hydraulic system as example. Additional examples presented by high-order transfer functions with and without time-delay, have been considered in the next one section. After that, conclusions have been given.

## PROBLEM DEFINITION

Ziegler - Nichols method based on frequency response is experimental approach and due to that various difficulties are possible during its performance [8,9]. First of all, there are difference between tuning and functioning phase of the system. Namely, experimental tuning of the PID controller is carried out according configuration in Fig. 1. It is highly suitable for design of PID controllers for high-order systems, because it enables avoiding model reduction.

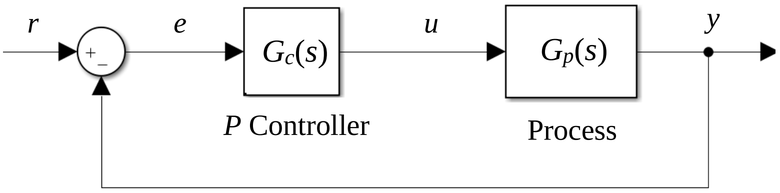

**Fig. 1.** Configuration for controller tuning according Ziegler - Nichols method [8,9]

The meaning of variables in the Fig. 1. are: $r$ – reference value, $e$ – error, $u$ – manipulated value, $y$ – controlled value (system response).

Controller is set to only proportional (P) term, by turning off its integral and derivative terms. Then P term is increasing until system response get into oscillating region. In that boundary stable state ultimate period $T_u$ of oscillation should be determined. Ultimate gain $K_u$ is known from value of P term, which caused response's oscillation. Using these two ultimate values and expressions in the Table 1, parameters of the PID controller (1) can be determined [8,9].

$$G_c(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) = K_p + \frac{K_i}{s} + K_d s \tag{1}$$

Where: $K_p \equiv$ P – proportional gain, $K_i \equiv$ I – integral gain, $K_d \equiv$ D – derivative gain, $T_i$ – integral time constant and $T_d$ – derivative time constant.

**Table 1.** Parameters of PID controller according Ziegler - Nichols method of frequency response [8,9]

| Controller | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|
| P | 0,5 $K_u$ | - | - |
| PI | 0,4 $K_u$ | 0,8 $T_u$ | - |
| PID (parallel) | 0,4 $K_u$ | 0,5 $T_u$ | 0,125 $T_u$ |
| PID (serial) | 0,3 $K_u$ | 0,157 $T_u$ | 0,25 $T_u$ |

According this method, in the tuning stage, feedback given in the configuration in Fig. 1, can contain only proportional term, in order to system can reach boundary stable state (oscillation in the response). Significant problem is appearing in the functioning stage of systems, which contain sensors (in the feedback) that are integral and/or derivative types. In that cases, corrections of expressions for PID controller design in Table 1 are required.

## HYDRAULIC SYSTEM AS EXAMPLE

Hydraulic systems are good solutions for enabling high forces in the industry. Therefore, design of control systems for two similar electro-hydraulic systems will be considered in this section.

## System description

Very representative example in the sense of above mentioned problem is hydrostatic power transmitter, which has been described as a high-order system without time delay and explained in detail in [10,11]. Its functional schema is given in the Fig. 2, where all components of this electro-hydraulic positioning servo system can be seen. This control system is consisted of two parts: power transferring part and control device for servo pump (SP). Obviously, this is controlling of angular position $\vartheta_m$ of the hydro motor (HM) by changing of volumetric flow rate of servo pump (SP). Flow rate of servo pump (SP) depends on position of the tilting plate, which is driven by linear hydraulic motor (LHM) that is controlled by electro-hydraulic directional servo valve (EHDSV). Reference value is determined by setting input voltage $U_u$.

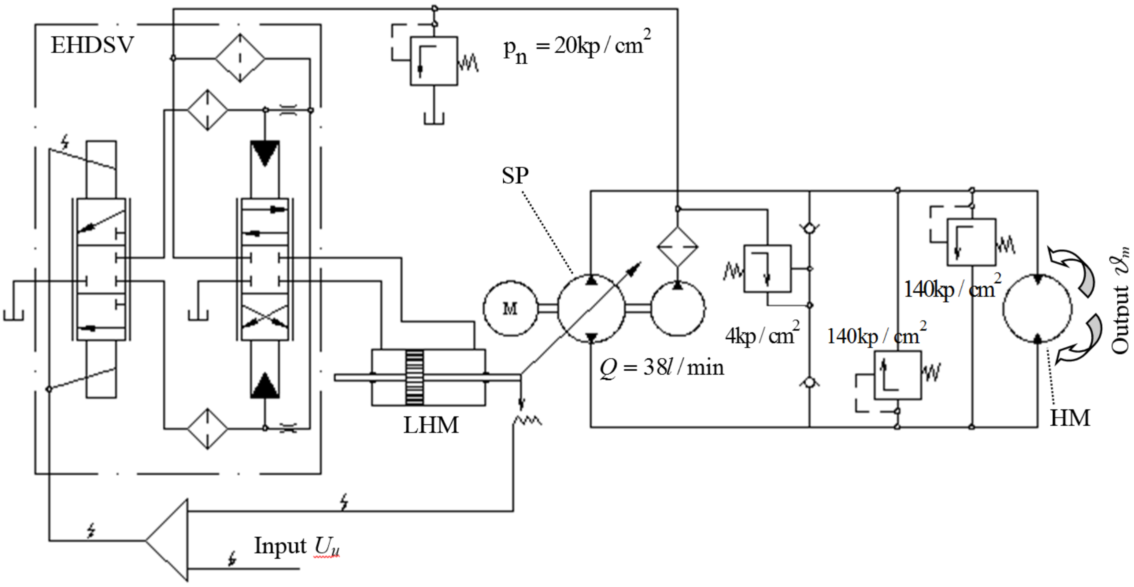

**Fig. 2.** Shema of the electro-hydraulic positioning servo system [10,11]

Open loop transfer function of considered servo system (Fig. 2) is given by (2) [10] and its block diagram can be seen in Fig. 3 [10].

$$G_p(s) = \frac{0.29}{0.00003s^2 + 0.0198s + 1} \cdot \frac{0.0012s^2 + 0.007s + 1}{0.0006s^3 + 0.0025s^2 + s} \tag{2}$$

As it can be seen in (2), considered servo system is modelled as fifth-order system without time delay. This characteristic is not going along with basic Ziegler - Nichols method, because they developed expressions for calculation of PID controller parameters for systems with time delay.

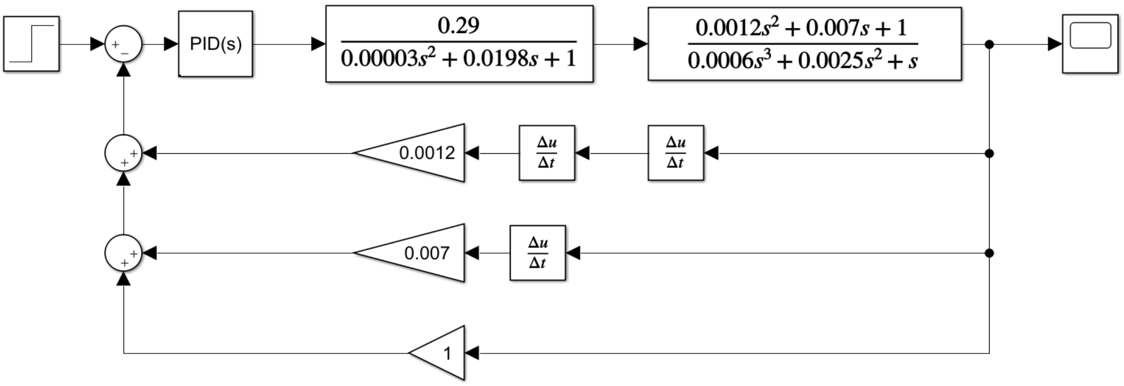

**Fig. 3.** Block diagram of the electro-hydraulic positioning servo system [10]

To obtain better system dynamic behavior, beside position sensor, velocity sensor (tachogenerator) and accelerometer (pressure sensor) have been introduced into control loop, as Fig. 3 shows.

## Procedure for controller design

At first, based on Ziegler - Nichols frequency method, configuration in Fig. 1, with unit feedback, is used to make system response oscillate. Additional sensors, as in Fig. 3 have been avoided in this tuning stage, because they didn't lead to boundary stable state of the system. Gradually increasing of proportional gain *P*, according configuration in Fig. 1, gives oscillatory response (angular position $\vartheta_m$) shown in Fig. 4. Reference value is set to be $r = 4$ rad.

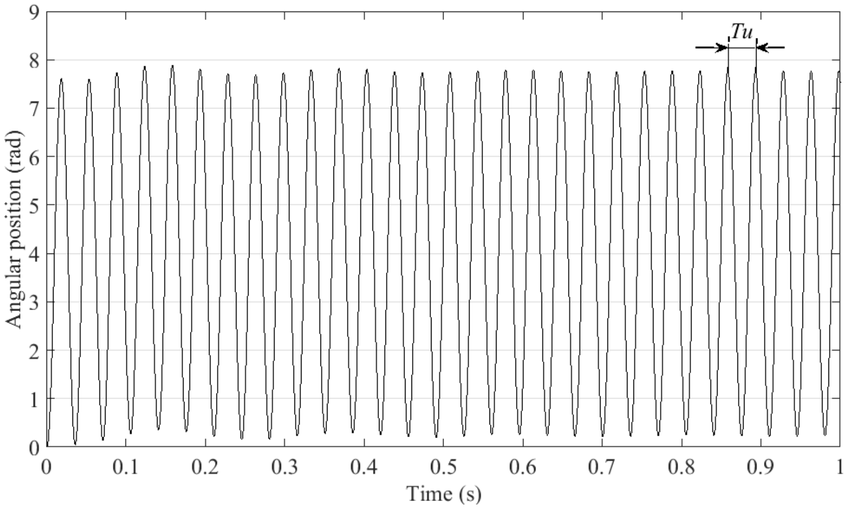

**Fig. 4.** Oscillatory response of the system (2)

Now, ultimate gain $K_u$ and ultimate period $T_u$ are known as $K_u$=1072.6 and $T_u$= 0.035(s). Mentioned problems appears because introducing $K_u$ and $T_u$ into expressions in the Table 1 and calculating parameters of PID controller based on them, didn't give appropriate system response. This is caused with differences in the feedback in tuning and functioning stage of the system. After that, a lot of simulations (Fig. 3) of system functioning had been performed in order to determine corrected expressions for determining of PID controller terms and they are shown in Table 2. Corrections haven't been suggested for serial PID controller because it wasn't considered in this investigation, i.e. parallel PID controller has been used.

**Table 2.** Corrected expressions for PID controller according to Ziegler - Nichols method of frequency response

| Controller | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|
| P | $K_u$ /(100÷150) | - | - |
| PI | $K_u$/170 | 150 $T_u$ | - |
| PID (parallel) | $K_u$/170 | 150 $T_u$ | 0.125 $T_u$ |
| PID (serial) | 0.3 $K_u$ | 0.157 $T_u$ | 0.25 $T_u$ |

According them, values of controller parameters are following:
P=7.1507
P1=10.726
P=6.3094, I=1.2018
P=6.3094, I=1.2018, D=0.0276
It is important to say that *P* controller was calculated using highest value in the suggested range $K_u$/150, while P1 controller has been calculated with lowest value in the mentioned range $K_u$/100. This range was adopted for response speed adjusting. Responses of the investigated electro-hydraulic

system (Fig. 5) were obtained by introducing obtained PID parameters into configuration shown in Fig. 3 and thay are generally good. Obviously, response controlled by P1 controller is faster than response controlled by P controller. PI and PID controllers cause practically the same responses due to low value of the derivative term. Namely, this figure shows responses for characteristic tuned controllers, but P controller is the best one due to absence of overshoot and steady state error and short enough rise time.

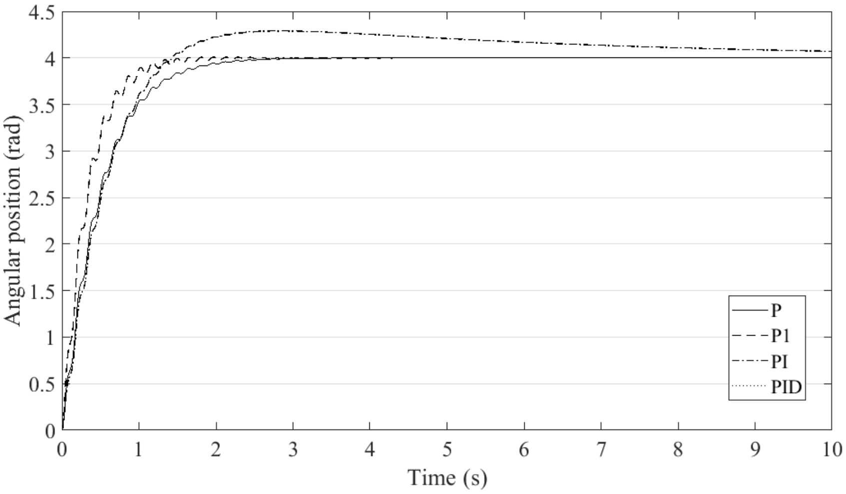

**Fig. 5.** Responses of the electro-hydraulic system (2)

### Changed system

To prove validity of the corrected expressions for PID controller design, some changes have been introduced into mathematical model (2) of servo system (Fig. 2.) and presented by (3). Transfer function (3) has been changed by different coefficients of the numerator and denominator, but not structurally. Therefore, it can present different system.

$$G_P(s)=\frac{0.87}{0.000015s^2+0.0099s+1}\cdot\frac{0.0036s^2+0.021s+1}{0.0003s^3+0.0012s^2+0.5s} \tag{3}$$

By carrying out above explained Ziegler - Nichols method for system (3), ultimate gain $K_u$ and ultimate period $T_u$ are determined $K_u$=60.793 and $T_u$= 0.025(s). Using again expressions in the Table 2. parameters of the controller has been calculated, as follows:
P=0.4053
P1=0.6079
P=0.3576, I=0.0954
P=0.3576, I=0.0954, D=0.0011

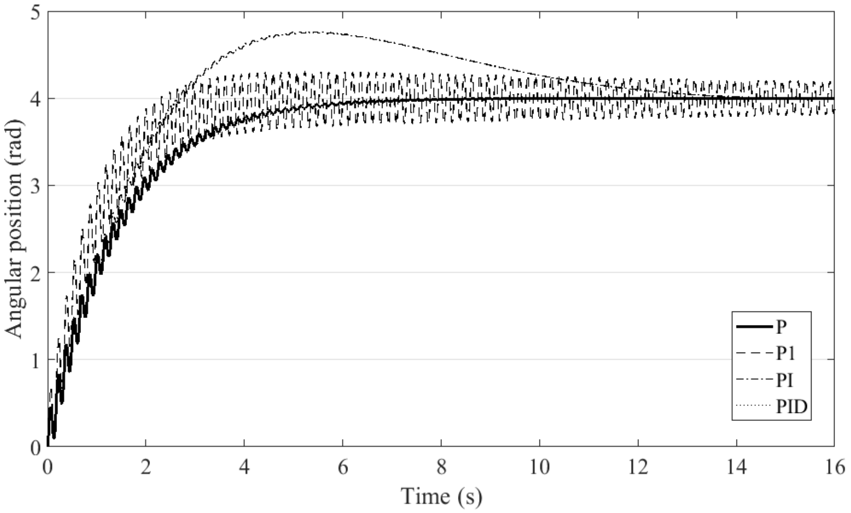

**Fig. 6.** Responses of the changed system (3)

The meanings of controller's marks are the same as for system (2) in the previous example. Simulations of system functioning were performed as in previous example. These controllers give responses in the Fig. 6. Responses in Fig. 6. put in the foreground P controller as the best solution for the system (3). The reasons are the same like in above example, i.e. absence of overshoot and steady state error and short enough rise time. Other types of controllers is not good enough due to oscillations or overshoot higher then 10%.

## ADDITIONAL EXAMPLES

In this chapter, two additional examples will be considered in order to explore high-order systems without pole in the origin of complex plane. The first one is given by (4) [7].

$$G_P(s)=\frac{1}{s^4+4s^3+6s^2+4s+1} \tag{4}$$

In addition to that transfer function (4) don't have pole in the origin of complex plane, this system is without time delay. So, there are two differences regarding basic Ziegler - Nichols method.

Method that extend Ziegler - Nichols, called Tyreus - Luyben method, has been used for calculation of PID controller parameters for system (4) due to enabling better system responses. Expressions for parameter calculation is tabulated in Table 3.

**Table 3.** Parameters of PID controller according to Tyreus - Luyben method [9]

| Controller | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|
| P | - | - | - |
| PI | $K_u/3.2$ | 2.2 $T_u$ | - |
| PID | $K_u/2.2$ | 2.2 $T_u$ | $T_u/6.3$ |

Differences in the defined preconditions for this method usage cause corrections of its expressions too. These corrections have been suggested based on results obtained from simulations of system functioning. Mentioned expressions is given in Table 4. It is important to say that corrections of expressions were made only for proportional term, i.e. integral and derivative term are determined using unchanged expressions in Table 3.

**Table 4.** Corrected expressions for PID controller according Tyreus - Luyben method

| Controller | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|
| P | - | - | - |
| PI | 0.1 $K_u$ | 2.2 $T_u$ | - |
| PID | 0.1 $K_u$ | 2.2 $T_u$ | $T_u$/6.3 |

Tyreus - Luyben method (Table 3.)
PI P=1.25, I=0.0905
PID P=1.8182, I=0.1316, D=1.8124

Tyreus - Luyben method, corrected (Table 4.)
PIcor P=0.4, I=0.0905
PIDcor P=0.4, I=0.1316, D=1.8124

System responses in the Fig. 7. are result of applying structure in Fig. 3. for system (4) with tuned controllers PI, PID, PIcor and PIDcor. Without any additional explanations, it is noticeable that controllers tuned using corrected expressions enable significantly better responses.

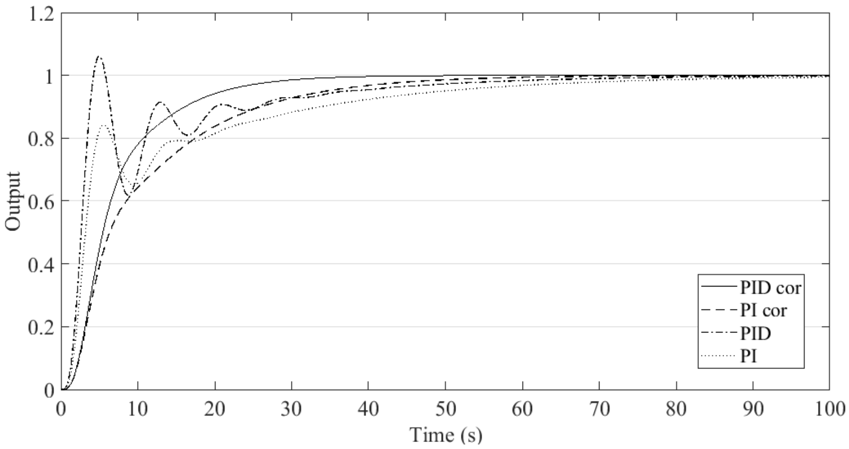

**Fig. 7.** Responses of the system (4)

One more high-order system (5) [7] is considered below, but with time delay.

$$G_P(s)=\frac{1}{s^5+2s^4+5s^3+7s^2+4s+1}e^{-2s} \tag{5}$$

The same procedure as for system (4) has been carried out. Controller's parameters and simulated responses (Fig. 8.) follow.

Tyreus - Luyben method (Table 3.)
PI P=0.5084, I=0.0194
PID P=0.7395, I=0.0282, D=1.3969

Tyreus - Luyben method, corrected (Table 4.)
PIcor P=0.1627, I=0.0194
PIDcor P=0.1627, I=0.0282, D=1.3969

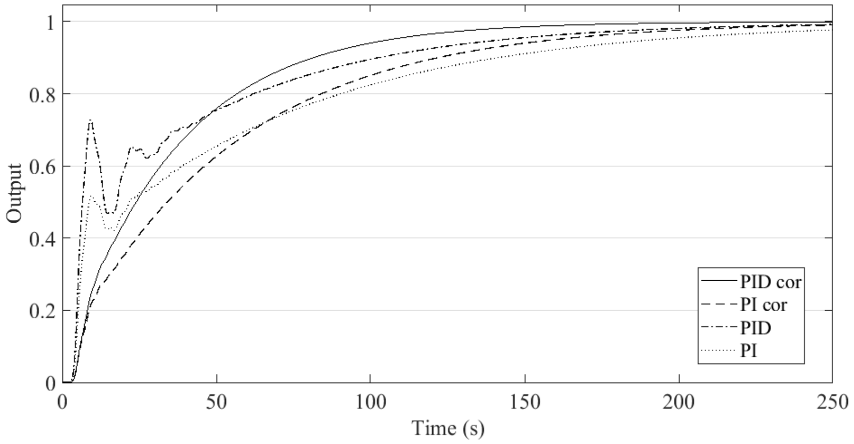

**Fig. 8.** Responses of the system (5)

From Fig. 8, is also evident that corrected expressions give controllers, which enables so much better responses. In this way applicability of suggested expressions for calculation of PID controller terms has been proved.

## CONCLUSION

Suggested corrections of the Ziegler - Nichols method and its upgraded version (Tyreus - Luyben method) enable calculation of controller parameters for high-order systems without their model reduction. This approach enables avoidance data loss that can be important for reflection of system behavior. In this way, differences between tuning and functioning stage of the system have been overcome, because system closed loop can contain various types of sensors. Effectiveness of the determined expressions have been proven on the various examples: with and without pole in the origin of complex plane and with and without time delay. Obtained responses have good quality indicators. Moreover, ranges for the particular expressions for controller terms calculation have been determined in order to achieve influence to the response speed.

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