

Original Article

Designing of Digital PID Controller for Blood Glucose Level of Diabetic Patient by Using Various Tuning Methods

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Received Date: 03 January 2022

Revised Date: 06 February 2022

Accepted Date: 18 February 2022

Abstract - The main objective of this paper is to design the digital PID controller for injecting insulin externally to the diabetic patient for maintaining a healthy blood glucose level. We have designed PID controllers using various tuning rules for examining the best performance in terms of different time response parameters like Overshoot, settling time & rise time, etc. Various tuning methods used for designing PID in this paper are the Ziegler Nichols method and the IPDT method. We have also made approximate mathematical modelling of blood glucose levels. Finally, we convert the conventional PID controller into a digital PID controller.

Keywords - Ziegler Nichols, IPDT, Diabetic patient, MATLAB simulation.

I. INTRODUCTION

Nowadays, blood sugar, or we can also say Diabetes, is a common disease in the world. The recent data is observed that in 2014 report, 29.1 million people have diabetes. Diabetes is a systemic endocrinal disorder that Hyperglycemia and Glycosuria with Ketonuria characterizes. The higher blood glucose level of the diabetic patient above 180 mg/dl is the type of patient suffering from Hyperglycemia. Another terminology is Hypo-glycemia, which is caused by less than 70 mg/dl blood glucose level of the diabetic patient. Hyperglycemia causes long-term diseases like heart attack, kidney damage, eye-related problem and nerve damage [1].

Diabetes is generally of two different types. The one commonly affected is Type 1 Diabetes mellitus, and the other is Type 2 Diabetes mellitus [3]. Type 1 Diabetes mellitus is caused by an absence of Beta cells in the pancreas. Due to the absence of beta cells in the pancreas, insulin deficiency in the human body is created. That's why we provide the external insulin to maintain the blood sugar(glucose) level at the healthy range, i.e., 3.8 mmol/L to 5.6 mmol/L (or in

terms of mg/dl is 70 to 120 mg/dl). It is also referred to as Insulin Dependent Diabetes Mellitus (IDDM) [3].

Type 2 Diabetes Mellitus starts with insulin resistance. Due to this insulin resistance condition, Beta-cell doesn't produce insulin properly, which requires the diabetic patient. It can be generated in persons with an excess amount of body weight. It is also referred to as Non-insulin Dependent Diabetes Mellitus (NIDDM) [2].

Therefore, in Type 2 Diabetes, a low probability exists that externally injected insulin can cure it. But in Type-1 Diabetes appropriate amount of externally injected insulin can maintain a healthy level of blood glucose. Here are the various ways of the external process to inject insulin. One process is to inject the insulin through the injection by any human being, and the other process is to inject insulin using an automatic digital PID controller. This controller detects the actual glucose level of the patient & compares it with a healthy level which is the set point. Depending upon the difference of the actual & healthy level of blood glucose, the PID controller injects the amount of insulin that is needed for the blood glucose level of a diabetic patient for coming to the normal range [6].

I. MATHEMATICAL MODELLING OF HUMAN BLOOD GLUCOSE LEVEL

In the blood of the human being, the amount of insulin present decides the level of Glucose. If more insulin is present, then the Glucose level remains at a healthy level. The given differential equation can verify the approximate mathematical modeling of blood glucose. The differential equation of blood glucose is shown below – [2]

$$r(t) = \frac{d^3c(t)}{dt^3} + 6 \frac{d^2c(t)}{dt^2} + 5 \frac{dc(t)}{dt} \quad (1)$$

Where $r(t)$ is the response of the blood glucose-insulin system, i.e., the amount of insulin input to the system, and $c(t)$ is the input of the blood glucose-insulin system, i.e., the actual measured level of glucose in blood [2]. The



differential equation (1) is converted into the Laplace domain using the forward transform technique with zero initial conditions [12].

$$C(s) \rightarrow L\{c(t); t \rightarrow s\} \quad (a)$$

$$R(s) \rightarrow L\{r(t); t \rightarrow s\} \quad (b)$$

Equation (a) and equation (b) are put into equation (1), we get the equation in the term of S domain, which is –

$$R(s) = s^3C(s) + 6s^2C(s) + 5sC(s) \quad (2)$$

Now taking C(s) common in the above equation (2) and solving the equation in terms of R(s)/C(s), the transfer function, which is denoted by G_c(s), becomes.

$$G_c(s) = \frac{1}{s^3+6s^2+5s} \quad (3)$$

The above equation (3) shows the Transfer function of the blood glucose equation for a diabetic patient [2]. By using Triangle approximation (modified first-order hold), we convert the above equation (3) into discrete function in Z-domain as shown below:

$$G_c(z) = \frac{3.707e^{-005}z^3+0.003635z^2+0.00032252z+2.587e^{-005}}{z^3-2.511z^2+2.06z-0.5488} \quad (4)$$

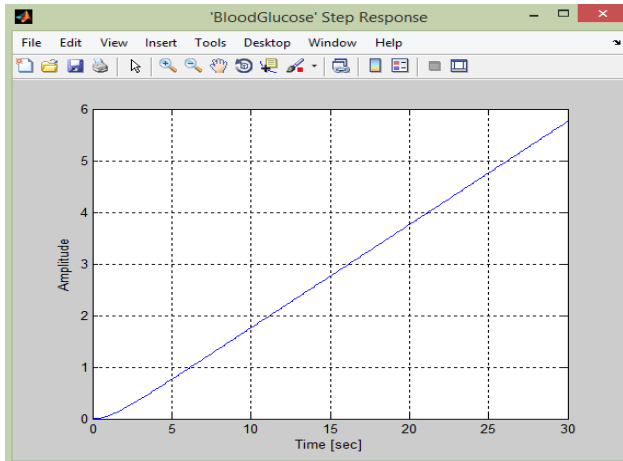


Fig. 1 Input step response of blood glucose-insulin system

The input step response of the blood glucose-insulin system is shown in figure 1. It can be seen in the form of the step response graph that the release of insulin by the insulin system increases with an increase in time, which is undesirable and is needed to be controlled. Therefore, an appropriate PID controller is needed to be designed for it.

The above figure reveals that although the system is stable, the settling time and overshoot are very high. So practically, when it is implemented, the insulin injection amount may increase instantaneously, which can create serious problems in the human body. It also may take a very large amount of time to bring a steady glucose level and injected insulin.

Therefore, the PID controller is designed to improve the time response parameters like overshoot and settling time in the next section.

II. DESIGNING OF DIGITAL PID CONTROLLER

Digital PID controller is a widely used application in industries, and it can also be used for medical purposes. This PID controller has been used 90 per cent in the industrial sector because it gives less settling time, improved transient response, less overshoot time, and it should be reliable. The equation of PID controller is [11-15] –

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \quad (5)$$

Where u(t) is controller output response, K_p is proportion gain of the system, K_d is the derivative gain of the system, K_i is the integral gain of the system stand for error which is SP-MV (SP is set-point and MV is measured value), t is instantaneous time, and τ is an integral variation from 0 to t. And the PID controller in the Laplace domain is-

$$L(s)=K_p + \frac{K_i}{s} + K_d s \quad (6)$$

Where L in the S domain represents the complex number of frequencies [8], using this blood glucose equation (3) in the digital PID controller, we find out the PID parameter by using various tuning methods like Ziegler Nichols and the IPDT tuning method.

III. ZIEGLER-NICHOLS TUNING METHOD

To obtain PID controller parameters by using the Ziegler and Nichols method formed by two empirical methods in 1940 [10].

1. Non-first order plus dead time situations.
2. Detailed intense manual calculations.

To calculate the tuning parameters of the PID controller, we use the following procedure:

For feedback loop or closed loop, we follow these steps:

- a. For finding the value of K_u, the integral and derivative action should be removed. Integral time (T_i) must be set to a large value (or 999), and derivative controller (T_d) must be set to 0.
- b. Changing the setpoint creates a small disturbance in the loop. Until the oscillations have a common amplitude, keep adjusting the proportional gain by increasing or decreasing.
- c. The gain value (K_u) and oscillation (Pu) period should be recorded.
- d. The necessary settings of the PID controller can be determined by plugging the appropriate values in the Ziegler-Nichols.[4]

Table 1. Closed-loop calculation of K_p, K_i, K_d .

	K_p	K_i	K_d
PID	$0.58K_u$	$0.83P_u$	$0.125P_u$
PI	$0.45K_u$	$0.5P_u$	
P	$0.5K_u$		

Table 2. Open loop calculation Of K_p, K_i, K_d

	K_p	K_i	K_d
PID	$1.2K_o$	$2\tau_{dead}$	$0.5\tau_{dead}$
PI	$0.9K_o$	$3.3\tau_{dead}$	
P	K_o		

The open-loop is also known as the Process Reaction method because it can test the process of open-loop reaction to bring about the change in the variable control output. These steps are as follows:

- (i). Open-loop step test must be performed.
- (ii). By studying the process reaction curve dead time or transportation lag (τ_{dead}), time for the response to change or the time constant (τ), and the value at which the system reaches the steady-state (M_0) for a step-change X_0 .

$$K_0 = \frac{X_0}{M_u} * \frac{\tau}{\tau_{dead}} \quad (7)$$

To calculate the tuning parameters of the PID controller, put the values of reaction time and lag rate into the Ziegler-Nichols open-loop tuning equation. [4]

IV. DIGITAL PID CONTROLLER TUNING WITH ZIEGLER-NICHOLS

For finding the digital PID controller by using the tuning method of Ziegler Nichols method, the block diagram of digital PID controller with blood glucose equation is shown in figure 1. The related parameters of PID controller by using Ziegler Nichols method are, $K_p = 3.25316$, $K_i = 0.882044$, $K_d = 2.99957$. Putting the value of K_p, K_i, K_d , we obtain the Ziegler-Nichols equation for blood glucose level, after that we convert the equation into discrete domain by using Triangle approximation (modified first-order hold) with sampling time is 0.1sec we get $G_z(z)$ –

$$\frac{0.0004436z^4 + 0.007341z^3 - 0.02238z^2 + 0.007553z + 0.003113}{z^4 - 3.488z^3 + 4.527z^2 - 2.588z + 0.5488} \quad (8)$$

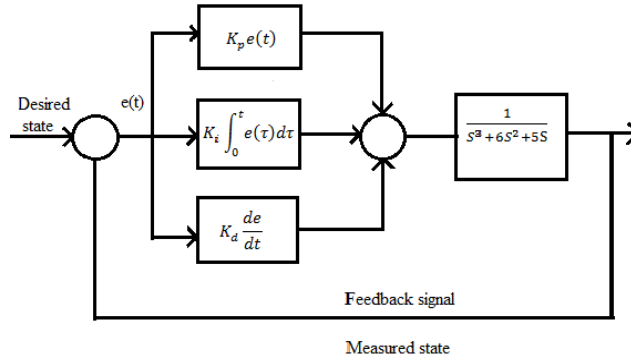


Fig. 2 Block diagram of PID controller with blood glucose-insulin system

This parameter shows it improve the settling time; it also shows the overshoot value is a little bit large, but the system's performance is efficient. [5]

V. IPDT TUNING METHOD

This method has many industrial models that can be approximated in integer plus time delay. The IPDT combines integer processes with time delay or dead time. The IPDT equation, which is shown below [7,9],

$$G_{IPDT}(s) = \frac{K}{s} e^{-Ls} \quad (9)$$

K is the gain factor, and L is a time delay or dead time. To find the value of K , where K is the ratio of change in output to change in input and also to find the value of L , $L = T_2 - T_1$ where T_1 and T_2 are the time instances in seconds

which is taken from the step response obtained having a particular steady-state gain.

In the IPDT tuning method, there is no need for the integrator to remove the steady-state error. To minimize the overshoot time, we can use the PD controller [7]. After getting the value of K and L putting these values in equation (9), we get the value of $G_{IPDT}(s)$. After the approximate modelling of IPDT using the Ziegler-Nichols method, we find out the value of K_p, K_i , and K_d .

VI. DIGITAL PID CONTROLLER TUNING WITH IPDT METHOD

We find out the value of PID parameters K_p, K_i, K_d by using the tuning method of IPDT. Using the tuning method of IPDT method in digital PID controller of blood glucose-insulin system, those parameters values are, $K_p=5.70833$, $K_i=3.19258$, $K_d=4.0415$. Putting the value of K_p, K_i, K_d , we

obtain the IPDT equation for blood glucose level, after that we convert the equation into discrete domain by using Triangle approximation (modified first-order hold) with sampling time is 0.1sec we get $G_i(z)$ –

$$\frac{0.006024z^4 + 0.01034z^3 - 0.03009z^2 + 0.0098z + 0.004159}{z^4 - 3.479z^3 + 4.511z^2 - 2.581z + 0.5488} \quad (10)$$

This parameter value shows that the system's settling time is less, which means it takes less time to settle down the response, or we can also say that it is a fast or without time-consuming system.

VII. RESULTS

The step response of the complete system (equation 8) developed using the Ziegler-Nichols method is shown in figure 5. The step response shows that the overshoot is 1.24%, and the settling time is 28 seconds (approx..).

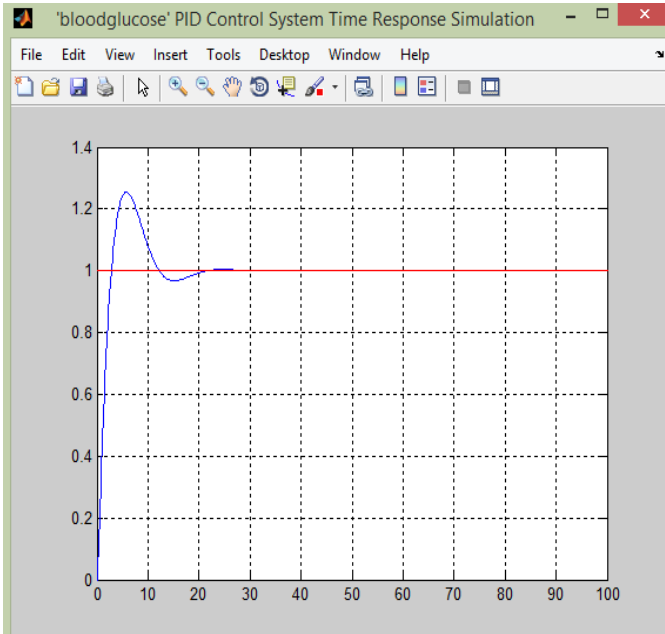


Fig. 3 Step response of blood glucose-insulin system by using Ziegler-Nichols method.

The step response of the system (equation 10) developed using the IPDT method is shown in figure 4. The overshoot is 1.38%, which is higher than that of Ziegler-Nichols and the settling time is 23 seconds (approx..), which is lower than Ziegler-Nichols.

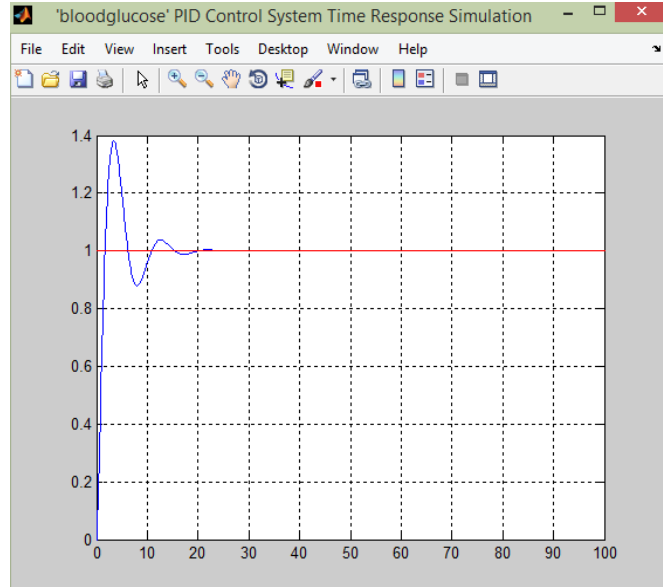


Fig. 4 Step response of blood glucose-insulin system by using IPDT method.

VIII. DISCUSSION

The overshoot and settling time is very high for the blood glucose system, but when the PID is designed and tuned using IPDT, the overshoot is limited to 41.68%, and settling time is also minimized up to 14.2469sec. PID, tuned using the Ziegler-Nichols method, results in a very low overshoot of 26.67% and a slightly higher settling time of 17.9192 sec. Finally, the blood glucose system is converted into a discrete domain using the Triangular approximation (modified first-order hold) method.

IX. CONCLUSION

While designing a PID controller for blood glucose maintenance by injecting external insulin, the time response parameter must be considered. As we have discussed, the overshoot of the PID controller designed using the Ziegler-Nichols method is very less suitable for tuning PID. But in IPDT tuning, the designed PID imparts a very high overshoot, whereas the settling time becomes comparatively less. Therefore, IPDT can't be used for tuning as it may endanger a patient's life by injecting a very large amount of insulin initially due to overshoot. After tuning the PID, it is essential to convert the analogue PID to digital PID as hardware implementation of digital PID is very easy in the minimized area. Further tuning of PID after implementation also becomes very easy and accurate.

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