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Original Article

Amelioration of Digital PID Controller Performance for Blood Glucose Level of Diabetic Patient

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Abstract *– The background of this paper discusses the design of a digital PID (Proportional-integral derivative) controller for controlling the blood glucose level of a diabetic patient. The objective is to design a digital PID controller for external insulin injection, which can inject insulin to the patient accurately to sustain the blood glucose level of a diabetic patient. The patient's blood sugar level is considered as input variable & injected insulin level is considered as output variable, which is to be controlled. A dynamic model is constructed & a transfer function is defined for this system. The Proportional, Integral & Derivatives coefficients are found using various tuning rules. The conventional Ziegler Nicholas method produces a very high overshoot that can endanger a patient's life. Therefore, other efficient tuning techniques like Chien-Hrones-Reswick (set-point regulation) and Chien-Hrones-Reswick (distribution regulation) methods are used to find the Proportional, Integral & Derivative coefficient. The tuning responses are studied & parameters are compared. The best response given by the PID is converted into Digital PID. Different transformation methods are studied to convert the conventional PID into the digital PID controller.*

Keywords - *Digital PID controller, Diabetic Patients, Blood Glucose, Chien-Hrones-Reswick (set-point regulation), Chien-Hrones-Reswick (distribution regulation), MATLAB simulation.*

I. INTRODUCTION

In 2014, the Centers for Disease Control and Prevention (CDC) National diabetes report says 29.1 million US children and adults are afflictions from diabetes. Diabetes is a long-term disease that can happen because the body does not respond or properly produce insulin. Insulin is a hormone that needs to absorb the body cell and use glucose to fuel body cells. Due to diabetes, many problems occur, such as coronary heart disease, weakness, kidney problems, non-traumatic amputations, blindness, secondary infection, etc. There are 3 types of diabetes: Type-I diabetes, Type-II diabetes, and Gestational diabetes.

Type-II diabetes occurs when our body cells have become resistant to the sway of insulin. Due to this increase in blood glucose level, it mostly occurs over the age of 45 years and overweight person. It can also take place family history of diabetes, so it is called non-insulin-dependent diabetes or adult-onset.

Gestational diabetes generally arises in pregnant women during pregnancy. Aspects include pregnancy over the age of 25, being overweight at the time of pregnancy, and Excessive intrauterine growth during pregnancy. During pregnancy, hyperglycemia increases, so it affects the offspring. Hyperglycemia occurs due to high blood glucose levels above 120 mg/dl, while hypoglycemia occurs less than 60 mg/dl.

Type-I diabetes is caused by the death of a beta cell in the pancreas, so due to the absence of beta cells pancreas does not produce insulin as a body requirement (healthy blood glucose level is between 60mg/dl to 120mg/dl). This type of diabetes mostly occurs in childhood or adolescence, also called childhood diabetes or insulin-dependent diabetes. Insulin-dependent diabetes shows it can be easily diagnosed by inject-insulin to control the blood glucose level.
Here we are using an automatic digital proportional integral derivative (PID) controller to control the appropriate amount of healthy blood glucose level of a diabetic patient. If a diabetic patient has a blood glucose level above or below the set point so that this digital PID controller first senses the blood glucose level if it is above or below blood glucose, then it automatically controls the blood glucose level in the normal range by giving the appropriate amount of external insulin.

II. MATHEMATICAL MODELING OF BLOOD GLUCOSE LEVEL FROM DIFFERENTIAL EQUATION

Consider the blood glucose equation by obtaining a differential equation. The differential equation of blood glucose equation as given below [4, 12]-

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

We convert this differential equation into the Laplace domain using the forward Laplace transform. This transform can be applied as-

$$C(s) \to L\{c(t); t \to s\} \tag{2}$$

$$R(s) \to L\{r(t); t \to s\} \tag{3}$$

By applying this substitution, we get

$$R(s) = s^3C(s) + 6s^2C(s) + 5sC(s) \tag{4}$$

Simplifying this above equation in transfer function form, we get-

$$Gc(s) = \frac{R(S)}{C(S)} = \frac{1}{S^3+6S^2+5S} \tag{5}$$

This equation (5) shows the transfer function of the blood glucose level of a diabetic patient. Simulating this equation in Matlab, we get step response of blood glucose level of the diabetic patient as shown in figure 1. This figure shows the blood glucose-insulin system has taken more settling time to settle down to steady-state, which means that the system takes more time to reach a steady-state. The steady-state error value is also high, so we can use a digital PID controller to overcome the steady-state error, and we can also get an accurate step response with less rise time.

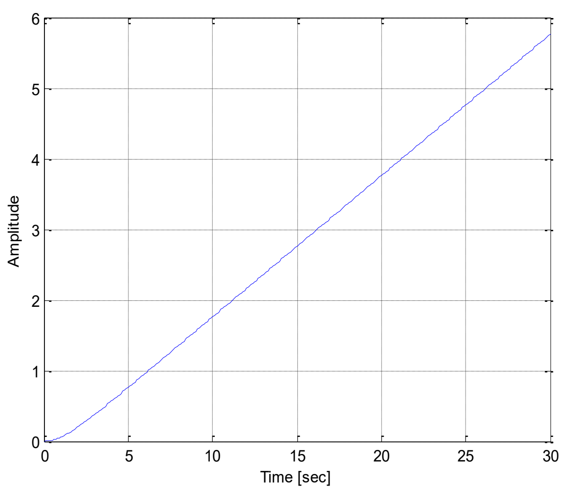

Fig. 1 Input step response of blood glucose level of the diabetic patient.

We also see the stability plot in figure (2) and bode plot in figure (3) of the blood glucose level of a diabetic patient. The stability plot shows the system is stable, so we can improvise the system performance to apply PID controller with various tunning methods like Ziegler-Nichols and cohen-coon method.

III. DESIGNING OF CONTROLLER

To design the digital PID controller for determining the error where the error is the difference between the glucose sensor's measured value and the desired glucose value. The equation for PID controller is [5, 11-15],

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt} e(t) \tag{4}$$

Where u(t) is output response, t is instantaneous time, τ is the integration variable vary from 0 to t, and e is the SP-MV error where SP is the set point of glucose and MV is the measured value of glucose.

Kp is proportional gain and depends on the system's present value. Ki is an integral gain, and it depends on the past accumulate value of the system. Kd is derivative gain, and it depends on future or expected value.

For equation (4), the transfer function of the PID controller is-

$$Gc(s) = kp\left(1 + \frac{1}{sTi} + sTd\right) \tag{6}$$

Where Ti is integral time and Td is derivative time.

The approximate modelling blood glucose-insulin system using the PID controller equation (6) is shown in figure 4.

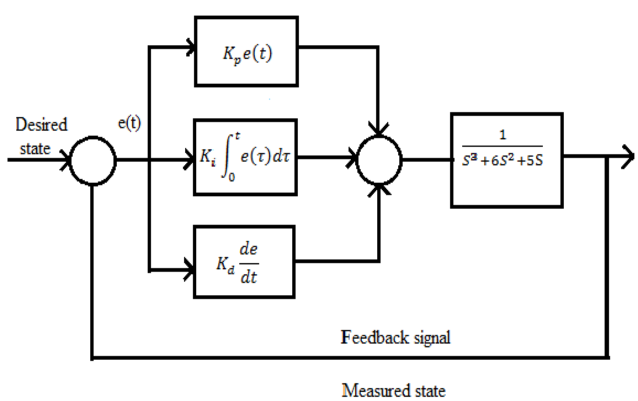

Fig. 2. Block diagram of blood glucose-insulin system with Digital PID controller

For finding the gain parameters like Kp, Ki, and Kd, the tuning methods like Ziegler –Nichols and Cohen-coon method are used then the best response parameter performance between them is compared.

IV. CHIEN-HRONES-RESWICK TUNING TECHNIQUE

The modified version of the Ziegler-Nichols method is Chien-Hrones-Reswick (CHR) method [8]. In 1952, this method was developed by Chien-Hrones-Reswick, which gives a better way to select a compensator for control applications. There are two forms of CHR: Chien- Hrone-

Reswick (setpoint regulation), also known as CHR-1 and Chien-Hrone-Reswick (disturbance rejection). According to Chien-Hrones-Reswick suggestion, controller parameters are tuned in the industrial process. The setpoint response method is summarized in Table 1 and Table 2, showing the controller parameters. These controller parameters have 0% and 20% overshoot, summarized in Table 1 and Table 2 [8-10].

Table 1. CHR-1 method of calculating K_p, K_i and K_d [8]

Overshoot	0%			20%		
Controller	K_p	K_i	K_d	K_p	K_i	K_d
PID	0.6/a	T	0.5L	0.95/a	1.4T	0.47L
PI	0.35/a	1.2T	-	0.6/a	T	-
P	0.3/a	-	-	0.7/a	-	-

Table 2. CHR-2 method of calculating K_p, K_i and K_d [8]

Overshoot	0%					
Controller	K_p	K_i	K_d	K_p	K_i	K_d
PID	0.95/a	2.4L	0.42L	1.2/a	2L	0.42L
PI	0.6/a	4L	-	0.7/a	2.3L	-
P	0.3/a	-	-	0.7/a	-	-

A. Tuning of PID controller by using Chien-Hrones-Reswik (Distribution Rejection) method

By using the above blood glucose equation (5), we apply in the equation of PID controller by using the Chien-Hrones-Reswik (Distribution Rejection) method we get the value of controller parameters as given below

K_p=3.25316, K_i=0.882044, K_d=2.51964

Now we solve the equation (5) and equation (6), we get the expression is-

$$Gc(s) = \frac{kds^2 + \text{kps} + \text{ki}}{s^4 + 6s^3 + (5 + kd)s^2 + \text{kps} + \text{ki}} \quad (12)$$

Putting the value of Kp, Ki, Kd, we obtain the Chien-Hrones-Reswik (Distribution Rejection) transfer function blood glucose level is –

$$\text{H(S)} = \frac{2.52\text{s}^2 + 3.257\text{s} + 0.884}{\text{s}^4 + 6\text{s}^3 + 7.52\text{s}^2 + 3.257\text{s} + 0.884} \quad (13)$$

B. Tuning of PID controller by using Chien-Hrones-Reswik (set-point regulation) method

By using the above blood glucose equation (3), we apply in the equation of PID controller by using the Chien-Hrones-Reswik (set-point regulation) method we get the value of controller parameters as given below

K_p=2.57541, K_i=2.00374e-008, K_d=2.23218

Now we solve the equation (3) and equation (5), we get the expression is-

$$Gc(s) = \frac{kds^2 + \text{kps} + \text{ki}}{s^4 + 6s^3 + (5 + kd)s^2 + \text{kps} + \text{ki}} \quad (14)$$

Putting the value of Kp, Ki, Kd, we obtain the Chien-Hrones-Reswik (Set-point regulation) transfer function for blood glucose level, H(s) is -

$$\frac{2.232\text{s}^2 + 2.575\text{s} + 2.004e^{-008}}{\text{s}^4 + 6\text{s}^3 + 7.2322\text{s}^2 + 2.5754\text{s} + 2.0037\text{e}^{-008}} \quad (15)$$

V. ZERO-ORDER HOLD CONVERSION METHOD

We need to accurately discretise the system for staircase inputs in the time domain. The process of discretization of the continuous-time system being applied with the zero-order holds method is shown below,

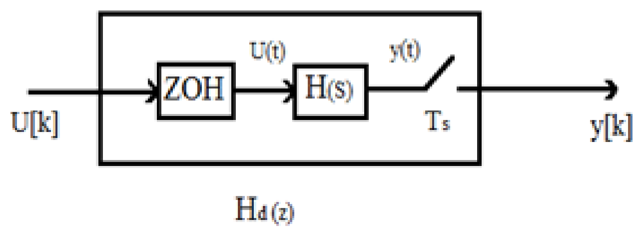

Fig. 3 Block diagram of discretized the continuous-time system with the zero-order hold method

By applying the constant value of U[k] over the zero-order hold (ZOH) block and this ZOH block produce the continuous-time input U(t), which can be seen in figure 3.

$$U(t)=u[k],\ kT_s \le t \le (k+1)T_s \quad (16)$$

U(t) is the input signal to the continuous system H(s) and generates the output y(t), and the sampling of y(t) every T_s seconds generate the output y[k].

On the other hand, the discrete system $H_d(z)$ is also converted into continuous system H(s). The following limitation of ZOH discrete-to-continuous conversion: Discrete to continuous (d2c) cannot be converted into LTI systems with poles at z = 0.

ZOH discrete to continuous(d2c) conversion produces a higher-order continuous-time system while discrete-time LTI systems have negative real poles.

This ZOH method can be used to discretize MIMO or SISO continuous-time systems with time delays. This method shows an accurate discretization for systems with output and input delays with no internal delays.

After that, we convert the Chien-Hrones-Reswick (distribution rejection) equation (13) and Chien-Hrones-Reswick (set-point regulation) equation (15) into discrete domain by using Zero-order hold with sampling time is 0.1 sec, we get $G_z(z)$ for equation (13) is–

$$\frac{0.01082z^3 - 0.01105z^2 - 0.007844z + 0.008132}{z^4 - 3.491z^3 + 4.534z^2 - 2.591z + 0.5488} \quad (17)$$

And for equation (15), $G_z(z)$ is-

$$\frac{0.009544z^3 - 0.009926z^2 - 0.0068552z + 0.007237}{z^4 - 3.494z^3 + 4.538z^2 - 2.5932z + 0.5488} \quad (18)$$

VI. FIRST-ORDER HOLD (FOH) METHOD

We can desire the accurately discretised system for piecewise linear inputs in the time domain. The first-order hold method is slightly different from zero-order hold by the principle of hold mechanism. In first-order hold method uses linear interpolation to convert the sample u[k] into continuous input u(t).

$$u(t) = u[k] + \frac{t-kTs}{Ts}\,(u[k+1]-u[k]),\ kTs \leq t \leq (k+1)Ts \quad (19)$$

The First-order hold method is a more suitable and accurate system driven by smooth inputs than the zero-order hold method. It differs from the standard causal first-order hold method called triangle approximations, also known as a ramp-invariant approximation.
This FOH method for system time delay is the same as the zero-order hold method. This method can also be used to discretize MIMO or SISO continuous-time systems with time delays.

After that, we convert the Chien-Hrones-Reswick (distribution rejection) equation (13) and Chien-Hrones Reswick (set-point regulation) equation (15) into discrete domain by using First-order hold with sampling time is 0.1 sec, we get $G_z(z)$ for equation (13) is–

$$\frac{0.003746z^4 + 0.006345z^3 - 0.01882z^2 + 0.006196z + 0.002602}{z^4 - 3.491z^3 + 4.534z^2 - 2.591z + 0.5488} \quad (20)$$

And for equation (15), $G_z(z)$ is-

$$\frac{0.003307z^4 + 0.005509z^3 - 0.0167z^2 + 0.005572z + 0.002313}{z^4 - 3.494z^3 + 4.538z^2 - 2.593z + 0.5488} \quad (21)$$

VII. IMPULSE-INVARIANT MAPPING

This impulse-invariant mapping conversion accurately gives discretised systems for impulse train inputs in the time domain. Impulse-invariant mapping introduces a phase mismatch at higher frequencies and a shift in DC gain of the discretized system. This phase mismatch occurs due to aliasing effects, and this effect becomes more precise to increase the sampling time.

The aliasing effects become more prominent when the shift in DC gain of the system decreases with decreasing the sampling time. Due to this aliasing, impulse-invariant mapping is not good for matching the frequency response in a continuous-time system. We choose the bilinear transform for frequency response matching, such as the Tustin approximation.

This Impulse-invariant mapping with time delays can be used to discretize MIMO or SISO continuous-time system. This method shows an accurate discretization for continuous-time systems.

After that, we convert the Chien-Hrones-Reswick (distribution rejection) equation (13) and Chien-Hrones Reswick (set-point regulation) equation (15) into discrete domain by using Impulse-invariant mapping with sampling time is 0.1 sec, we get $G_z(z)$ for equation (13) is–

$$\frac{0.2006z^3 - 0.3762z^2 + 0.1763z - 9.786e^{-017}}{z^4 - 3.491z^3 + 4.534z^2 - 2.591z + 0.5488} \quad (22)$$

And for equation (15), $G_z(z)$ is-

$$\frac{0.1764z^3 - 0.3336z^2 + 0.1572z + 6.981e^{-017}}{z^4 - 3.494z^3 + 4.538z^2 - 2.5932z + 0.5488} \quad (23)$$

VIII. TUSTIN APPROXIMATION

The bilinear approximation or Tustin approximation uses the following equation as shown below:

$$Z = e^{sTz} = \frac{1+sTs/2}{1-sTs/2} \quad (24)$$

This above equation is related to z-domain and s-domain functions. By using c2d conversion, we use discretization $H_d(z)$ of continuous transfer function H(s) is given below:

$$H_d(z) = H_d(s'),\ s' = \frac{2}{Ts}\frac{z-1}{z+1} \quad (25)$$

Similarly, by using d2c conversion depends on the inverse transfer function, we use continuous H(s) of discrete transfer function $H_d(z)$ is given below:

$$H(s) = H_d(z'),\ z' = \frac{1+sTs/2}{1-sTs/2} \quad (26)$$

We use the Tustin approximation method for implicit matching of frequency domain between the continuous-time system and the discretized system. Tustin approximation can be used to approximate discretize MIMO or SISO continuous-time systems with time delays tau and $k{*}T_s$ is the time delay of integer portion which maps to delay the k^{th} sampling periods in the discretized system.

After that, we convert the Chien-Hrones-Reswick (distribution rejection) equation (13) and Chien-Hrones-Reswick (set-point regulation) equation (15) into discrete domain by using with Tustin approximation with sampling time is 0.1 sec, we get $G_z(z)$ for equation (13) is–

$$\frac{0.005088z^4 + 0.0006339z^3 - 0.009525z^2 - 0.0006004z + 0.00447}{z^4 - 3.486z^3 + 4.52z^2 - 2.578z + 0.5446} \quad (27)$$

And for equation (15), $G_z(z)$ is-

$$\frac{0.004477z^4 + 0.0004884z^3 - 0.008466z^2 - 0.0004884z + 0.003989}{z^4 - 3.489z^3 + 4.524z^2 - 2.579z + 0.5444} \quad (28)$$

IX. ZERO-POLE MATCHING EQUIVALENTS

Zero-pole matching equivalents have matched dc gain in discretized systems and continuous-time systems, it is only applied in SISO systems, and their pole and zeros transformation is shown below,

$$Zi = e^{SiTs} \quad (29)$$

Z_i, S_i is the *i*th zero or pole in the discrete-time and continuous-time systems, and the sampling time is T_s. This zero-pole matching with a time delay can be used to discretize SISO continuous-time system. This zero-pole matching is similar to the Tustin approximation in time delay.

After that, we convert the Chien-Hrones-Reswick (distribution rejection) equation (13) and Chien-Hrones-Reswick (set-point regulation) equation (15) into discrete domain by using Zero-pole matching equivalent with sampling time is 0.1 sec, we get $G_z(z)$ for equation (13) is–

$$\frac{0.01004z^3 - 0.008789z^2 - 0.01001z + 0.008822}{z^4 - 3.491z^3 + 4.534z^2 - 2.591z + 0.5488} \quad (30)$$

And for equation (15), $G_z(z)$ is-

$$\frac{0.008838z^3 - 0.007875z^2 - 0.008838z + 0.007875}{z^4 - 3.494z^3 + 4.538z^2 - 2.5932z + 0.5488} \quad (31)$$

X. RESULT

Table 3. Table showing the comparison between the outputs of Chien-Hrones-Reswick(distribution rejection) and Chien-Hrones-Reswick (setpoint regulation) techniques parameters.

Parameters	Chien-Hrones-Reswick(Distribution Rejection)	Chien-Hrones-Reswick(Set-Point Regulation)
Rise time (in seconds)	2.2858	4.8152
Overshoot (in percent)	29.41	0
Settling time (in seconds)	17.0751	6.3362

The step response for the blood glucose-insulin system using Chien-Hrones-Reswik (Distribution Rejection) method is shown in figure 4. From the step response graph, the overshoot is 29.41%, the rise time is 2.28 seconds (approx.), and the settling time is 17.07 seconds (approx.).

The step response for the blood glucose-insulin system using Chien-Hrones-Reswik (setpoint regulation) method is shown in figure 5. From the step response graph, the overshoot is 0%, the rise time is 4.81 seconds (approx.), and the settling time is 6.33 seconds (approx.). The output parameters are also listed in Table 3.

Apart from the rise and settling time, overshoot is the parameter that makes the blood glucose-insulin system the ideal Chien-Hrones-Reswik (setpoint regulation) method.

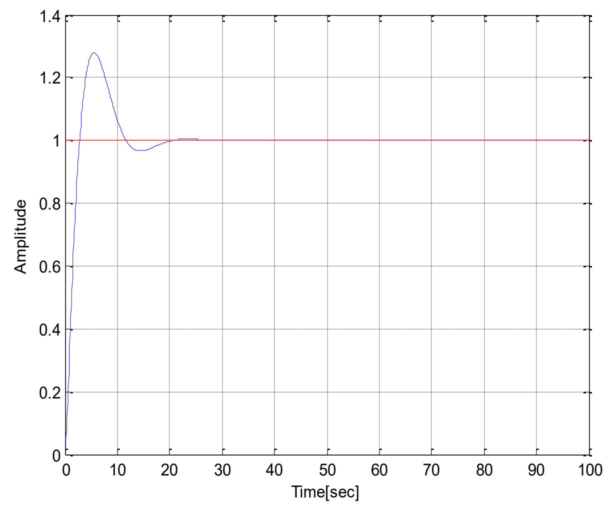

Fig. 4 Step response of blood glucose-insulin system by using Chien-Hrones-Reswik (Distribution Rejection) method

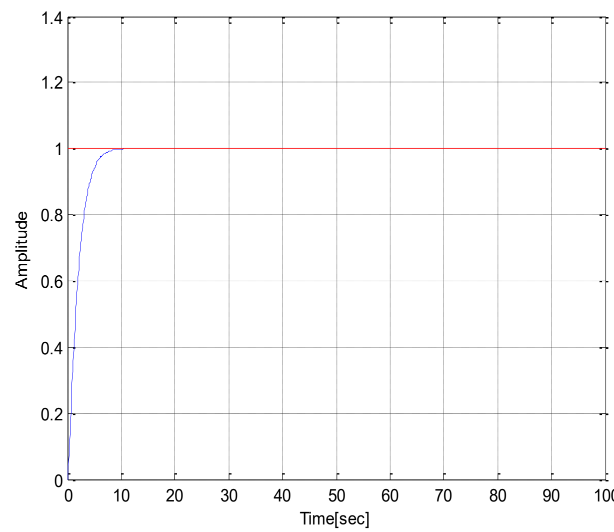

Fig. 5 Step response of blood glucose-insulin system by using Chien-Hrones-Reswik (setpoint regulation) method.

XI. CONCLUSION

Thus, we have successfully designed the Digital PID controllers for the blood glucose level of a diabetic patient, i.e., PID controller using various efficient tuning algorithms. Using traditional tuning methods, the integer order model of blood glucose level gave a very terrible response. From the results, it is obvious that Chien-Hrones-Reswick (Distribution Rejection) method yields a very high Overshoot, whereas Chien-Hrones-Reswick (Set-point regulation) method exhibits a zero overshoot and Chien-Hrones-Reswick (Set-point Regulation) method illustrate low settling time as compared to Chien-Hrones-Reswick (Distribution Rejection). The overshoot in the blood glucose level controller may create sudden high insulin levels and endanger a patient's life. Similarly, due to the high settling time in the Chien-Hrones-Reswick (Distribution Rejection) method, the blood glucose level takes a very long time to maintain the steady state, resulting in changes in life danger. Finally, these PIDs are converted into digital PIDs using various conversion methods. After tuning the PID, it is essential to convert the analogue PID to digital PID as we know hardware implementation of digital PID is very easy in the minimized area. Further tuning of PID after implementation becomes very easy, and the system becomes very accurate.

REFERENCES

[1] Kasper Dennis, Anthony Fauci, Stephen Hauser, Dan Longo, J. Jameson, Joseph Loscalzo, Harrison's principle of Internal Medicine ,18th Edition textbook, (2015).

[2] Kaveh Parisa, Shtessel Yuri, Higher Order Sliding Mode Control for Blood Glucose Regulation, Proceedings of the 2006 International Workshop on Variable Structure Systems, (2006) 12-16.

[3] Pinky Dua, Francis J. Doyle, and Pistikopoulos, Model-Based Blood Glucose Control for Type 1 Diabetes via Parametric Programming, IEEE Transactions on Biomedical Engineering, 53,(2006) 1478-1491.

[4] Anil kumar, Rekha Phadke, Design of digital PID controller for Blood Glucose monitoring system , International Journal of Engineering Research & Technology (IJERT), 3 (12) (2014) 307-311.

[5] Article: Ziegler-Nichls' open loop method, Finn Haugen Tech Tech, (2010).

[6] Amit kumar and K.K Garg, Comparison of Ziegler-Nichols, Cohen-Coon and fuzzy logic controllers for heat exchanger model , International Journal of Science, Engineering and Technology Research (IJSETR), 4(6) (2015) 1917-1920.

[7] J.A. Romero Perez, P. Balaguer Herrero, Extending the AMIGO PID tuning method to MIMO systems , IFAC conference on advances in PID control, (2012) 211-216.

[8] Neil Kuyenhove, PID tuning methods an automatic PID tuning study with Math Cad , Calvin college ENGR., 315 (2002).

[9] Amlan Basu, Sumit Mohanty, Rohit Sharma, Tuning of FOPID controller for meliorating the performance of the heating furnace using conventional tuning and optimization technique, International journal of electronics engineering research, 9(1) (2017) 69-85.

[10] Amlan Basu and Sumit Mohanty. FOPID Controller for Heating Furnaces: Meliorating the Heating Furnace System Performance Using PID Controller with Fractional Elements. (2016).

[11] Amlan Basu, and Sumit Mohanty. Tuning of FOPID (PI λ D μ) Controller for Heating Furnace. Int. J. Electron. Eng. Res 9 (2017) 1415-1437.

[12] Amlan Basu, Sumit Mohanty. Improving the Performance of PID Controller using Fractional Elements for Heating Furnace. Int. J. Electron. Eng. Res 9 (2017) 1415-1437.

[13] M Majid Hussain, Zulfiqar A Memon, M Akmal Chaudhary, M Siddique, An Innovative PID Controller in Conjunction with DC Electric Motor for Control of Hybrid Electric Vehicle , SSRG International Journal of Electrical and Electronics Engineering 7(7) (2020): 20-34.

[14] Phuong Chi Nguyen, Duc Quan Tran, Research on a PID Controller using PLC for a Heating System, SSRG International Journal of Electrical and Electronics Engineering, 5(1) (2018) 1-5.

[15] Rohit Sharma, Sumit Mohanty, Amlan Basu, Enhancement of digital PID controller performance for a blood glucose level of diabetic patients using disparate tuning techniques, Indian journal of science and technology, 10(17) (2017).