The Sensitivity Analysis and Settling Time Improvement of Cardiovascular System with the Incorporation of Ziegler-Nichols (Z-N) Rule

Soumyendu Bhattacharjee[1], AishwaryaBanerjee[1], SnehaDas[1], Dr.Biswarup Neogi[2]

Assistant Professor, Dept. of ECE, KIEM, Mankar, W.B, India [1]

Assistant Professor, Dept. of ECE, JISCE, Kalyani, W.B, India[2]

ABSTRACT:This paper presents the improvement of sensitivity of a system based on human heart, using PID tuning method. The Ziegler-Nichols method is used for PID tuning. For better result it is required to get desired performance specification in term of achieving maximum overshoot and specified settling time of the closed loop response .The proposed transfer function of heart and pacemaker is used in this paper with PID tuning to increase the sensitivity and Jury's test which is a stability test used for Z domain stability has also been applied to analyse that this system is also stable in Z domain.

KEYWORDS:PID Tuning, Sensitivity Analysis, Jury Stability Test.

I.INTRODUCTION

Electronics pacemaker for human hearts regulates the speed of a heart pump. A proposed close loop system that includes a pacemaker and a measurement of the heart rate is shown in fig below [1]. The process of selecting the controller parameters to meet given performance specifications known as controller tuning [2]. In spite of all the advances in control over the past 50 years the PID controller is still the most common controller The PID tuning method is used to get the better simulation of the proposed control system [3].The most important reason behind this PID tuning approach is due to its simple control structure and satisfactory results. Ziegler-Nichols suggested rules for PID controllers. Here Ziegler-Nichols (Z-N) tuning rule is chosen as it is easy to implement during MATLAB simulation. In this tuning approach Z-N (PID Tunning) Method is used which is efficient and appropriate a system.

II.SENSITIVITY ANALYSIS

The parameters of a control system have a tendency to vary due to change of environment conditions and this variation in parameters affects the desired performance of control system .The term sensitivity in relation to control system gives an idea of the system performance as affected due to parameter variations. Let the variable in a control system which changes its value be A such as output and this change is considered due to parameter variation of element K such as gain or feedback, then the control system sensitivity is expressed as-

Sensitivity$=\frac{\% \ change \ in \ A}{\% \ change \ in \ K}$

In mathematical terms sensitivity is written as: $S_K{}^A = \frac{\partial A/A}{\partial K/K}$

The Sensitivity function for the overall TF M(s) with respect to variation in G(s) is written as:
$S_G{}^M = \frac{\partial M(s)/M(s)}{\partial G(s)/G(s)}$
Or, $S_G{}^M = \frac{G(s)}{M(s)} \cdot \frac{\partial M(s)}{\partial G(s)}$

(a) Sensitivity for Open loop control system:In figure 1the basic block diagram of Close loop control systemare given below-
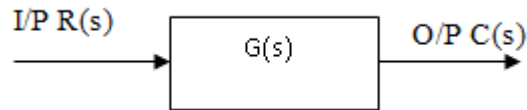
Fig 1: Open loop control system

For the system the overall TF is M(s) $=\frac{C(s)}{R(s)} = G(s)$

Or, $\frac{M(s)}{G(s)} = 1$

Differentiating M(s) w.r.t G(s),

$\frac{\partial M(s))}{\partial G(s)} = 1$

Therefore, the sensitivity for an open loop control system is obtained as:

$S_G{}^M = \frac{G(s))}{M(s)} \cdot \frac{\partial M(s)}{\partial G(s)} = 1$

(b)Sensitivity for Close loop control system: The basic block diagram of Close loop control system are given below in figure 2.
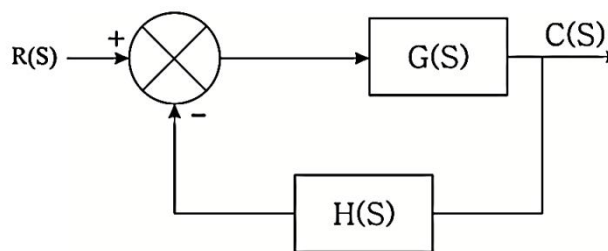

Fig 2: Close loop control system

For the system the overall TF is M(s) $=\frac{G(s)}{1+G(s)H(s)}$

Differentiating M(s) with respect to G(s),

$\frac{\partial M(s))}{\partial G(s)} = \frac{1}{[1+G(s)H(s)]^2}$

Therefore, the sensitivity for a closed loop control system is obtained as:

$S_G{}^M = \frac{G(s))}{M(s)} \cdot \frac{\partial M(s)}{\partial G(s)} = \frac{1}{1+G(s)H(s)}$

Comparing sensitivity functions, it is observed that the sensitivity of the overall TF with respect to forward path TF in the case of closed loop control system is reduced by a factor $1 + G(s)H(s)$ as compare to open loop system. [4]

(C) The sensitivity of overall TF M(s) with respect to feedback path TF:

The sensitivity of overall TF M(s) with respect to feedback path TF H(s) is written as:

$S_H{}^M = \frac{\partial M(s)/M(s)}{\partial H(s)/H(s)}$, Or, $S_H{}^M = \frac{H(s))}{M(s)} \cdot \frac{\partial M(s)}{\partial H(s)}$

For the closed loop control system the overall TF is M(s) $=\frac{G(s)}{1+G(s)H(s)}$

Differentiating M(s) with respect to H(s), $\frac{\partial M(s))}{\partial H(s)} = \frac{G(s)^2}{[1+G(s)H(s)]^2}$

Therefore $S_H{}^M = -\frac{G(s)H(s))}{1+G(s)H(s)}$

Comparing sensitivity functions, it is concluded that closed loop control system is more sensitive to variations in feedback path parameters than the variation in forward path parameters.

III.SENSITIVITY ANALYSIS FOR THE GIVEN SYSTEM

(a) Sensitivity of overall transfer function with respect to forward path is given by:

$$S_G{}^M = \frac{1}{1+G(s)H(s)} S_G{}^M = \frac{s^2+12s}{s^2+12s+12K}$$

Putting s= jω and K=10(given) [3] we get $S_G{}^M = \frac{-\omega^2+12j\omega}{-\omega^2+12j\omega+120}$

Considering ω = 1rad/sec, $S_G{}^M = \frac{-1+12j}{-1+12j+120} = 0.9$

(b)The sensitivity of overall TF(M) with respect to feedback path TF (H) is given by:

$$S_H{}^M = -\frac{G(s)H(s)}{1+G(s)H(s)} = -\frac{\frac{12K}{s^2+12s}}{1+\frac{12K}{s^2+12s}} = -\frac{12K}{(s)^2+12s+12K}$$

Putting s=jω and K=10, we get $-S_H{}^M = -\frac{120}{-\omega^2+12j\omega+120}$

Considering ω = 1ard/sec, $S_H{}^M = -\frac{120}{-1^2+2j+120} = -1.43$

IV.FREQUENCY DOMAIN ANALYSIS OF GIVEN SYSTEM

(a) Routh's stability criterion:
Routh's-Hurwitz criterion is a mathematical test that is a necessary and sufficient condition for the stability for linear time invariant or LTI system.
In Routh-Hurwitz Criterion stability, the system is stable if and only if all the elements in the first column have the same algebraic sign. The importance of the criterion is that the roots P of the characteristic equation of linear LTI system with negative real parts represent solution e^{pt} of the system that are stable. Thus this criterion provides a way to test whether a system is stable or not.
The characteristic equation, $a_0s^n+a_1s^{n-1}+\ldots\ldots\ldots a_{n-1}s+a_n = 0$
Where, $a_0 \neq 0$ and $a_n > 0$, and the co-efficient $a_0, a_1, a_2, \ldots\ldots\ldots\ldots$ are all of the same sign.

(b) Routh's array:

S^n	a_0	a_1	a_4	a_6…………
S^{n-1}	a_1	a_3	a_5	a_7
S^{n-2}	b_1	b_2	b_3	b_4
S^{n-3}	c_1	c_2	c_3	c_4
S^{n-4}	d_1	d_2	d_3	d_4
………	…………………	………………		
…………	………………	………………		
S^2	e_1	e_2		
S^1	f_1			
S^0	g_0			

Where the coefficients b_n are given below.
n -represents the positive numbers.
$b_1 = \frac{a_1a_2-a_0a_3}{a_1}$
$b_2 = \frac{a_1a_4-a_0a_5}{a_1}$

$b_3 = \frac{a_1 a_6 - a_0 a_7}{a_1}$ and so on.

The coefficient c_i and d_i are as follows,

$c_1 = \frac{b_1 a_3 - a_1 b_2}{b_1}$

$c_2 = \frac{b_1 a_5 - a_1 b_3}{b_1}$

$d_1 = \frac{c_1 b_2 - b_1 c_2}{c_1}$

$d_2 = \frac{c_1 b_3 - b_1 c_3}{c_1}$

Transfer Function of the system is $= \frac{K}{s\left(\frac{s}{12}\right)+1}$

For the system the overall Transfer Function is M(s) $= \frac{G(s)}{1+G(s)H(s)}$

M(s) $= \frac{12K}{s^2 + 12s + 12K}$

The characteristics equation is- $1 + \frac{12K}{s^2 + 12s + 12K} = 0$

$\frac{s^2 + 12s + 24K}{s^2 + 12s + 12K} = 0$

$s^2 + 12s + 24K = 0$

By Routh's Stability Analysis-

S^2 1   24K

 S   12   0

S^1 $\frac{288K - 0}{12}$ 0

288K/12=0

24K≥0

.

The range of K must be≥0

The given T.F is M(s) $= \frac{12K}{s^2 + 12s + 12K}$

The T.F of 2nd order system is- $\omega_n^2 / s^2 + 2\xi\omega_n s +- \omega_n^2$

Where ω_n = Natural Frequency of the system.

And ξ = Damping Factor of the system.

By comparing these two equations we get,

$\omega_n^2 = 12K$, $2\xi\omega_n s = 12s$, $\xi\omega_n = 6$, $\xi = \frac{6}{\sqrt{12K}}$

V. STABILITY ANALYSIS OF A CLOSED LOOP SYSTEM IN Z DOMAIN

The stability is the most important parameter in control system.Thus stability of a closed loop system is given as

$$M(z) = \frac{G(z)}{1+G(z)H(z)}$$

It can be determined from the location of closed loop poles in the Z plane which are the roots of the characteristic equation.

(a) Jury's Test:

Jury's test is used to analyse if any LTI(linear time invariant) system is stable in Z domain or not .To check whether a system is stable in Z domain first criterion is to check the characteristic equation against a number of specific rules and requirements.[5]

(b) Specific rules:

The characteristic equation D(Z)=$a_0 + a_1 z + a_2 z^2 + \ldots\ldots\ldots\ldots\ldots\ldots\ldots + a_N z^N$

Being the highest degree of the polynomial .This test determines the pole outside of the unit circle.

1: If Z=1 the system must be positive D(1)>0

2: If Z=-1 then $(-1)^N D(-1) > 0$

3: The value of constant term a_0 must be less than the highest coefficient a_N. $|a_0| < |a_N|$

4: Once Jury's array has been constructed it automatically satisfies the following conditions

$|b_0| > |b_{N-1}|$, $|c_0| > |c_{N-2}|$, $|d_0| > |d_{N-3}|$

(c) Jury's Array:

Row	Z^0	Z^1	Z^2	Z^3	Z^4	………..	Z^N
1	a_0	a_1	a_2	a_3	……..	………..	a_N
2	a_N	a_{N-1}	a_{N-2}	a_{N-3}	……..	………..	a_0
3	b_0	b_1	b_2	b_3	……..	………..	
4	b_{N-1}	b_{N-2}	b_{N-3}	b_{N-4}	……..	………..	
:	:	:	:	:	……..	………..	
:	:	:	:	:	……..	………..	
2N-3	v_0	v_1	v_3	v_4	……..	………..	

(d) Stability analysis of given transfer function in Z domain:Jury test is used to find out the stability in Z domain of the given system(Figure 3)
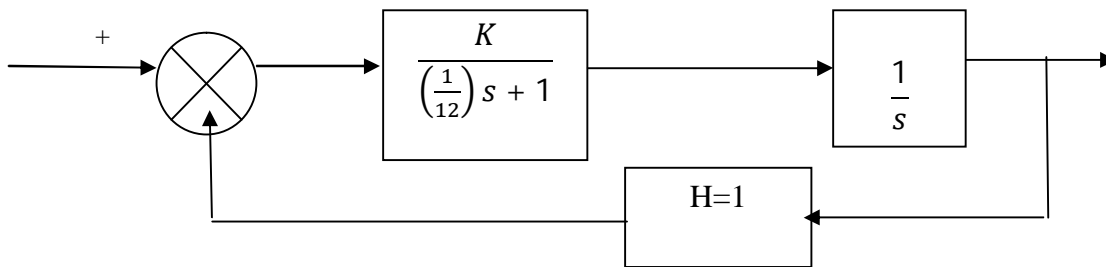

Fig 3:Heart Pace Maker System

In figure3 the heart-pacemaker system is given with a unity feedback, where the first block represents the transfer function of heart [6,7] and the second block connected in series represent the pacemaker system.

For a closed loop system , $\frac{C(s)}{R(S)} = \frac{G(S)}{1+G(S).H(S)}$

Here   G(s) $= \frac{K}{(\frac{1}{12})s+1} \times \frac{1}{S}$,&   H(s) =1

SO, $\frac{C(s)}{R(s)} = \frac{K/S(\frac{S}{12}+1)}{1+\frac{K}{S(\frac{S}{12}+1)} \times 1} = \{ \frac{K}{\frac{S^2}{12}+S+K} \} = \frac{12K}{s^2+12S+12K}$ ……..(i)

According to the bilinear transformation the relation between s and z is given as s $=\frac{2}{T}.\frac{(Z-1)}{(Z+1)}$

Putting the value of s in terms of Z in equation (i)

$=> \frac{12K}{[2/T \times (Z-1)/(Z+1)]^2 + 12[\frac{2}{T} \times \frac{Z-1}{Z+1}]+12K}$ ……..(ii)

Putting T =1sec& K=10 in equation (ii)

$=> \frac{120(Z+1)^2}{148Z^2+232Z+100} =\gg \frac{30(Z+1)^2}{37Z^2+58Z+25}$

D(z)=$37Z^2+58Z+25$……(iii) ,Applying rule 1 of Jury's stability in equation (iii)

D(1)= 37+58+25 =120>0

Applying rule 2 in equation (iii) $(-1)^N F(-1) = (-1)^2 [37-58+25] = 1 \times 4 = 4 > 0$

Applying rule 3 in equation (iii) $a_0 = 25$, $a_N = 37$, so $|a_0| < |a_N|$
Construction of Jury's array for equation (iii)

row	Z^0	Z^1	Z^2
1	25	58	37
2	37	58	25
3	b0	b1	

$a_0 = 25$, $a_1 = 58$, $a_2 = 37$
Here highest degree N=2
$b_0 = \begin{vmatrix} a0 & a2 \\ a2 & a0 \end{vmatrix} = \begin{vmatrix} 25 & 37 \\ 37 & 25 \end{vmatrix} = -744$
$b_1 = \begin{vmatrix} a0 & a1 \\ a2 & a1 \end{vmatrix} = \begin{vmatrix} 25 & 58 \\ 37 & 58 \end{vmatrix} = -696$

VI. APPROACH TO PID TUNNING

The proportional, integral, and derivative (PID) controller is widely used in the process industries due to its simplicity, robustness and wide ranges of applicability in the regulatory control layer. One survey of Desborough and Miller (2002) [8] indicates that more than 97% of regulatory controllers utilize the PID algorithm. Tuning a control loop is the adjustment of its control parameters (gain/proportional band, integral gain/reset, derivative gain/rate) to the optimum values for the desired control response.

(a) Manual Tuning:
If the system is online first all values are set to zero. Values are increased until the output of the loop oscillates and until the loop is acceptably quick to reach its reference after a load disturbance. However, too much will cause excessive response and overshoot. A fast PID loop tuning usually overshoots slightly to reach the set point more quickly. The main advantage of manual tuning is there is no requirement of math and online method.

(b) (Z-N) Ziegler- Nichols Method:
In 1942 Ziegler and Nichols described simple mathematical procedures for PID tuning [8]. Ziegler-Nichols tuning rule is a computational approach to search optimal sets of parameter values of PID controllers. Ziegler and Nichols proposed rules for determining values of parameters of PID controller - the proportional gain Kp, integral time Ti and derivative time T_d. Table 1 shows the values of Kp, Ti and T_d for PID Controller.[9]

Type of Controller	K_p	T_i	T_d
P	0.5 K_{cr}	∞	0
PI	0.45 K_{cr}	1/1.2P_{cr}	0
PID	0.6 K_{cr}	0.5P_{cr}	0.125P_{cr}

Table 1: Ziegler- Nichols Tuning Rule Based on Critical Gain K_{cr} and Critical Period P_{cr}

So, PID controller tuned by the Ziegler – Nichols rule gives, $G_c(s) = K_p(1 + \frac{1}{Tis} + T_d s)$

If the system has a known mathematical model (such as transfer function), then root locus method can be used to find out the critical gain K_{cr} and the frequency of sustained oscillations ω_{cr}, where $2\pi/\omega_{cr} = P_{cr}$

VII.SIMULATION RESULT AND SENSITIVITY ANALYSIS WITH PID TUNING APPROACH

PID controller consists of Proportional Action, Integral Action and Derivative Action. PID controllers can then be designed by using Ziegler-Nichols method. Tuning method for the basic PID control is commonly known as Ziegler-Nichols tuning rule (Z-N).
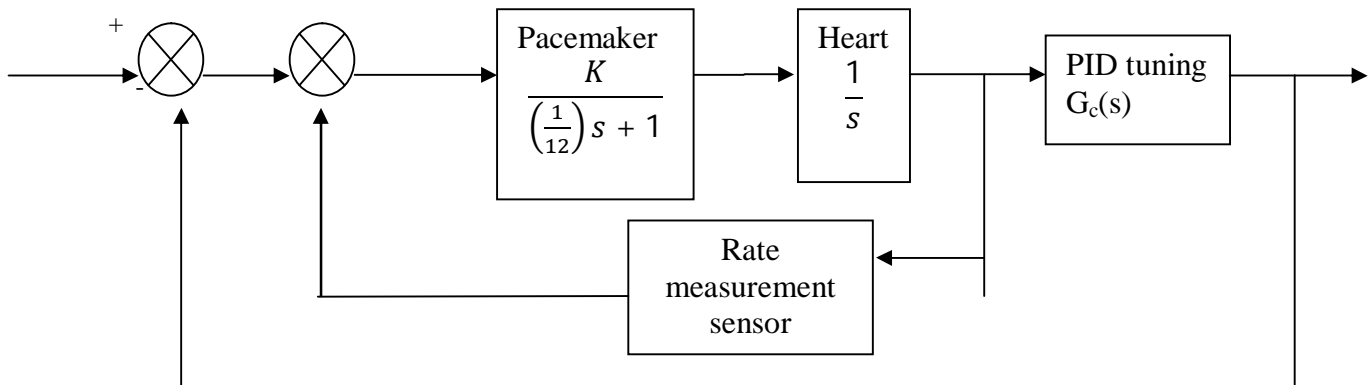

Fig 4: Heart Pacemaker System with PID Tuning Approach

Here the heart-pacemaker system is connected with a PID tuning shown in fig4 with a unity negative feedback. Now the PID [10] controller is to be designed to improve the sensitivity and settling time.

(a)PID controller design using Z-N method:

For the actual System the overall transfer function is-$G(s) = \frac{120}{s^2+12s+120}$ (putting K=10)

Now we are applying PID tuning method that is Ziegler Nichols(Z-N) Method.

The PID controller has the transfer function, $G_c(s) = K_p(1 + \frac{1}{T_i s} + T_d s)$

By Ziegler- Nichols Tuning Method, closed loop transfer function is

$\frac{C(s)}{R(s)} = \frac{K_p}{s^2+12s+120+K_p}$ [setting Ti = ∞ and Td = 0]

The value of $K_p$that makes the system marginally stable so that sustained oscillation occurs can be obtained by Routh's stability criteria. Since the characteristic equation for the closed-loop system is

$s^2 + 12s + 120 + K_p = 0$.

The Routh's array becomes as follows:

S^2 1   120

S 12 K_p

S^1 $\frac{1440-K_p}{12}$ 0

$1440-K_p=0$

Or, $K_p=1440=K_{cr}$, With gain $K_p$set equal to $K_{cr}= 1440$,

The characteristic equation becomes,

$s^2 + 12s + 120 + 1440 = 0$

$0r, s^2 + 12s + 1560 = 0$

To find the frequency of the sustained oscillation, s=jω is substituted into the characteristic equation. So it becomes,

$(jω)^2 + 12jω + 1560 = 0$,Or, $-ω^2 + 1560 = 0$

Or, ω=39.4, Pcr= 2π/ω =0.159

Referring to Table 1, Kp = 0.6Kcr = 864, Ti = 0.5Pcr = 0.079 , Td = 0.125Pcr = 0.019

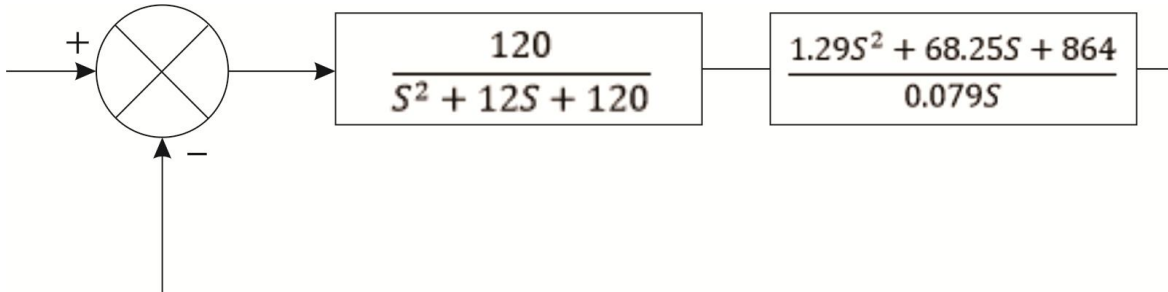The transfer function of the PID controller becomes, $G_c(s) = \frac{1.29s^2+68.25s+864}{0.079s}$

Fig 5: Given System with PID Tunning

In the figure 5 the transfer function of heart-pacemaker system is connected with the PID controller with negative feedback to examine the time response.

So, the closed loop tuned transfer function to examine the unit-step response of the system is

$$T(S) = \frac{G(s)Gc(s)}{1 + G(s)Gc(s)}$$

Or, $T(s) = \dfrac{154.8s^2 + 8190s + 103680}{0.079s^3 + 155.74s^2 + 8199.48s + 103680}$

(b) MATLAB code and Simulation result: The MATLAB code and step response(taking different value of damping factor) for Heart Pacemaker system without PID tuning and with PID tuning are given below.

```
clc;
forzy=0.54:0.1:1
sys=tf(120,[1 2*zy*sqrt(120) 120])
figure(1);
step(sys)

Kcr=240*zy*sqrt(120)
    w=sqrt(120+Kcr)
Pcr=2*pi/w
Kp=0.6*Kcr
    Ti=0.5*Pcr
    Td=0.125*Pcr
    sys2=tf([Kp*Ti*Td Kp*Ti Kp],[Ti 0])
    sys3=feedback(series(sys,sys2),1)
figure(2);
step(sys3)
end
```
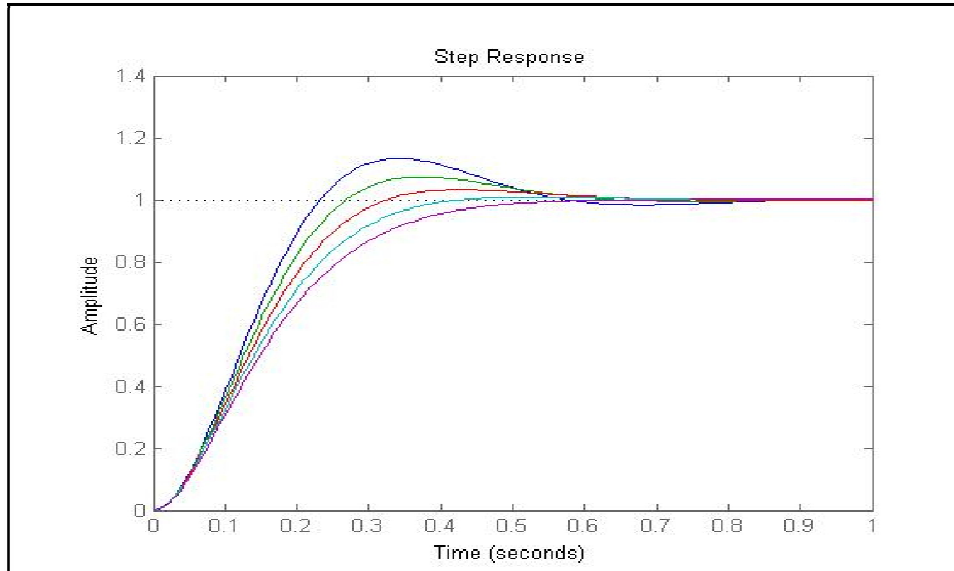
Fig 6: Time response analysis without PID tuning

Figure 6 and Figure 7 shows the simulation result of Time response analysis without PID tuning and Time response analysis with PID tuning for different values of damping factor.

(c)Sensitivity Analysis with PID Tunning:

Sensitivity of overall transfer function with respect to forward path is given by:

$S_G{}^M = \dfrac{1}{1 + G(s)\,H(s)}$, $S_G{}^M = \dfrac{0.079s^3 + 155.74s^2 + 8199.48s + 103680}{0.079s^3 + 310.54s^2 + 16389.48s + 207360}$

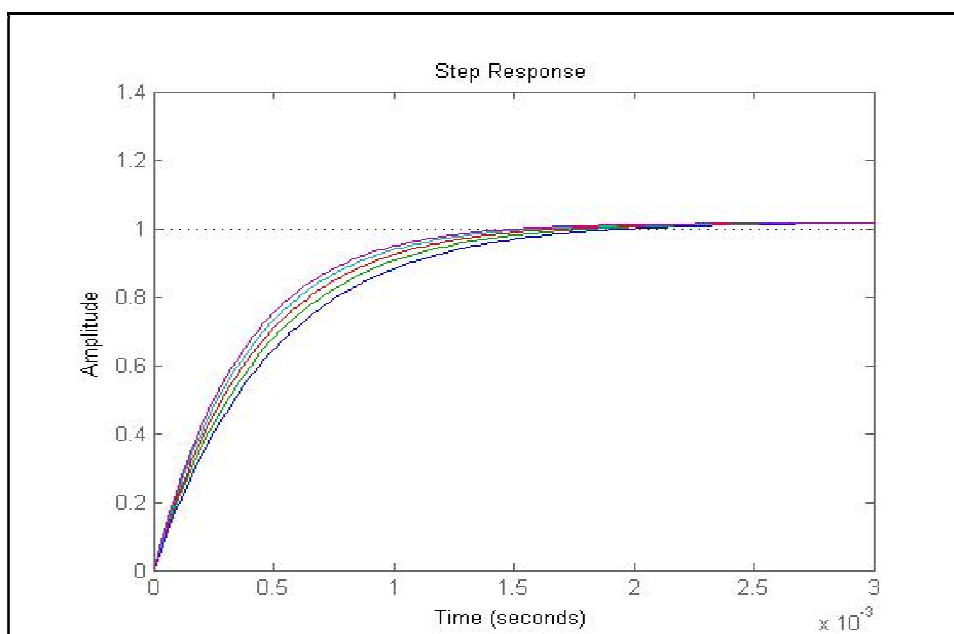Putting s= jωand ω = 1 , $S_G{}^M = \dfrac{103524.26 + 8199.401j}{207049.46 + 16389.401j} = 0.5$

Fig 7: Time response analysis with PID tuning

VIII.COMPARATIVE STUDY OF THE SYSTEM

(a) Simulation Results Analysis:

By studying response and stability criterion of the system, it is seen that after PID tuning i.e., the close loop configuration of Heart Pacemaker system has been improved a lot. The transfer function with PID tuning response shows least settling time with optimal overshoot.
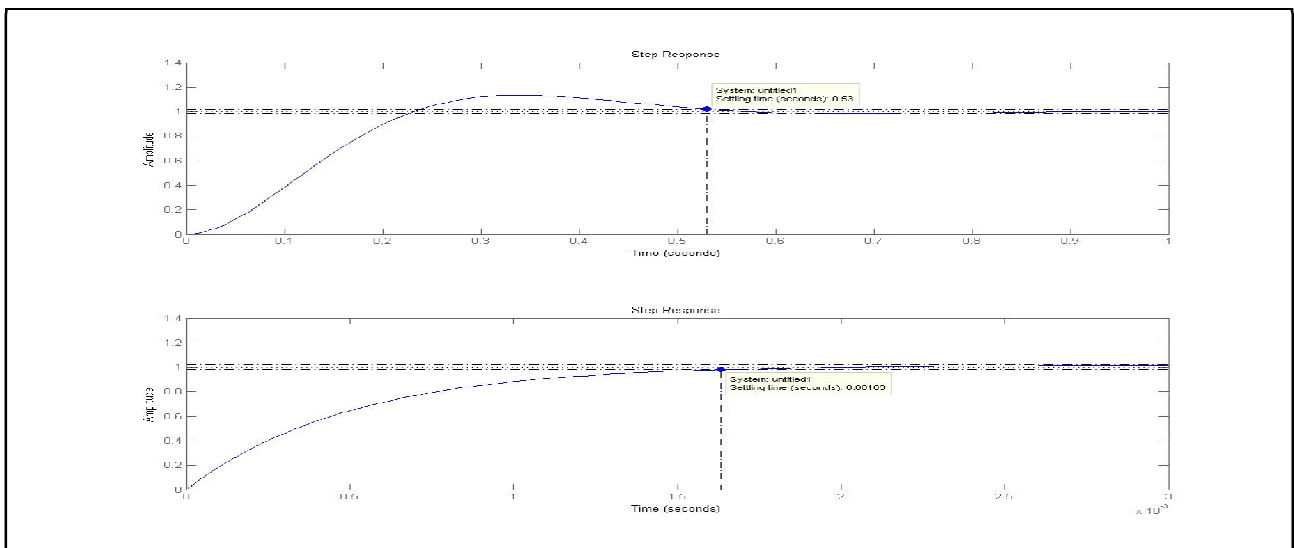

Fig 8: Comparative study of the system with damping factor 0.54

From figure 8, given below it is observed that, considering damping factor .54, the settling time without PID tuning is .53 second, where as the settling time with PID tuning is .0016 second. From figure 6 and figure 7 it is also observed that, for different values of damping factor the settling time and overshoot with PID tuning will be died down.

(b) Sensitivity Improvement:

From the above two figures that is fig 3 and fig 4 the calculated sensitivity of overall transfer function with respect to forward path is 0.9 and 0.5 respectively. As the definition says due to change of environment conditions the parameters of a control system may vary. This variation affects the desired performance of a control system. So, much the affect or sensitivity reduces the desired performance of the control system increases. Here the result is very much convenient for the heart pacemaker system.

IX.CONCLUSION

The Z-N tuning would serve as the basis for the upcoming new generation of PID technology as it provides improved performance, low cost, and training compared to other tuning methods like Cohen coon, trial and error method etc. It can be embedded into established, convenient generalized controller products. So from all the analysis done above in all calculation a conclusion can be made that the sensitivity and settling time of the proposed system increases as well as that system will be able working in both the S and Z domain. The MATLAB code is built considering its importance in analysing the behaviour of any system of the model type as described above and its tuned output response based on its input.

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BIOGRAPHY

SoumyenduBhattacharjee-Asst. Prof.& HOD, ECE Dept.,KANAD INSTITUTE OF ENGINEERING AND MANAGEMENT, Mankar, W.B, India. He is Headof Electronics & Communication Engineering Dept. in KIEM, Mankar. He has initiated hisPh.D (Enrolled in West Bengal University of Technology) under the supervision of Dr.B.Neogi. He received M.Tech degree in VLSI from B.E.S.U, Shibpur. Before that He obtained B.Tech in ECE from JIS College of Engineering, Kalyani. He is having a teaching experience of two years in AIEMD, Panagarh and five and a halfyears in KIEM, Mankar. He has been engaged as a successful examiner of WBUT curriculum. He wasalso awarded as for his innovative teaching idea from AIEMD Panagarh. His research interest includes Advance Control System, Digital Signal Processing, Microcontroller based EmbeddedSystem, VLSI,etc.

MS. AishwaryaBanerjee-Asst. Profof ECE department,KANAD INSTITUTE OF ENGINEERING AND MANAGEMENT, Mankar, W.B India. Presently she is pursuing her M-Tech degree in ECE under WEST BENGAL UNIVERSITY OF TECHNOLOGY. She has got her B-Tech degree from NetajiSubhash Engineering College, Garia under W.B.U.T inApplied Electronics And Instrumentation Engineering in the year of 2013.She has 6 months industrial experience related to PLC and SCADA and has done project works on PLC. She is presently working with K.I.E.M Mankar, For the last 6months in full time and last three months as a part time faculty.She has interest in research and development section (R&D) in field like biomedical instrumentation, control theory, microcontroller(8051), digital signal processing, industrial instrumentation.

MS. Sneha Das-She is currently working as an assistant professor in Dept. of Electronics & Communication Engineering in KIEM, Mankar. She is awarded the degree of M.Tech in Advanced Materials Science & technology from N.I.T Durgapur in 2014.Before that she received her B.Techh in Applied Electronics & Instrumentation Engineering from Asansol Engineering College under WBUT in 2012.She is having a teaching experience in KIEM of six months after completed her M.Tech degree. Her research interest includes Control Theory, Microwave, Process Control, Biomedical Engineering etc.

Dr.BiswarupNeogi is awarded PhD (Engineering) from Jadavpur University, India. He received M.Tech degree in ECE from Kalyani Govt. Engg.College in 2007. Before that He obtained B.E in ECE from UIT, The University of Burdwan in 2005.He has an experience on various project of All India Radio attach with the WebelMediatronics Ltd, Kolkata. He was a lecturer in ECE Dept, Haldia Institute of Technology. WB, India. He was working as a faculty in ECE Dept, Durgapur Institute of Advanced Technology & Management. Currently he is engaged with JIS College of Engineering, Kalyani as a Faculty member and flourished R&D related activity. Recently he is also engaged as a consultant executive engineer of YECOES Ltd, Hooghly, and attached as an advising body of different Engineering College under WBUT. His research interest includes Prosthetic Control, Biomedical Engineering, Digital Simulation, Microcontroller based Embedded System. He is guiding five Ph.D theses in this area. He has published about fifty several papers in International and National Journal and Conference conducted both in India and abroad. Additionally, he attached as a reviewer of several journals and yearly conference.