

# Modification of Howland Current Source using PID controller for Electrical Stimulation Related with Human Cardiovascular Disorder

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## ABSTRACT

Over the twenty years instead of magnetic stimulation, electrical stimulation is preferred and has widely been used as an investigation tool to find any disorder of human cardiovascular system and also been used in treatment purpose as the side effects are very low in case of electrical stimulation. Howland current source (HCS) is one of the most popular device among the countless device have been designed to provide electrical stimulation because of its stability and simplicity. The main objective of this work is to derive the transfer function of Howland current source which has been formulated in classical feedback approach when it works in linear region and then a proper PID controller has been designed using Z-N tuning rule to improve the system performance of it. An addition of pole to a system is introduced to avoid the disturbance in steady state part. The proposed design increases the speed of the system as transient response improves which leads the electrical stimulation faster.

**KEYWORDS:** Howland current source, Transfer function, PID Controller

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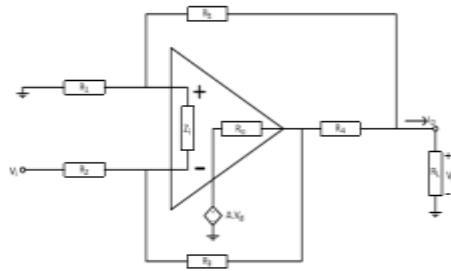
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## I. INTRODUCTION

The most important requirement in electrical stimulation process is to ensure that the charge is to be injected directly in the tissue which can be provided only by a current source, has constant amplitude over a wide frequency range. As a powerful source for exciting the tissues of cardiovascular system, Howland current source has been widely used over a wide frequency range for the last twenty years. In maximum application non-electrical engineers and technologists are using Operational amplifiers (Op-amps) to design their proposed model. In the previous research, Non idealities of the operational amplifiers and stray capacitances have been used for the design to reduce the amplitude but phase shift errors occurred at higher frequencies[1][2]. This paper is also helpful for someone who wants to calculate the transfer function of any circuit related with op amps. It is very important to calculate the transfer function of a system as controller cannot be designed without knowing system transfer function which will improve the system response for linear region. A proper PID controller has been designed using Z-N tuning rule to improve the system performance[3]. The probability density function due to small changes in the resistors of the circuit has also been calculated by using the analytical modeling.

## II. HOWLAND CURRENT SOURCE

Howland current source is very important device for electrical stimulation which is nothing but an operational amplifier topology effectively forms a linear differential voltage to current converter. The diagram for this circuit is given below in the figure 1. It does not require additional transistor or switch which leads the advantage over ordinary current source[4][5]. Another big advantage of this circuit is that, the load resistance can be grounded which is not possible for other current source.



**Figure 1: Represents the Howland current source (HCS)**

Considering all the resistors are perfectly equal and the operational amplifier (Opamp) with a large gain, the output current is given by  $-V_i/r$  (considering  $R_2 = R_3 = R_5 = R$ ,  $R_4 = r$  and  $R_1 = R + r$ ). This particular approximation gives a good result if the gain of Opamp is sufficiently large and load impedance is very small. To get good Common Mode Rejection Ratio (CMRR) and high output impedance it is mandatory to change the external resistors of the amplifiers[6]. To reduce frequency bandwidth of both output current and impedance, the non-ideal characteristics of the operational amplifiers (i.e., input impedance  $Z_i$ , and open-loop gain  $A$ , output resistance  $R_o$ ) should be observed.

### III. CIRCUIT NODAL EQUATIONS

Howland current source (HCS) can be characterized by the simple nodal Equations given in the equation (1)-(4), where  $V_2$  is the voltage at inverting input,  $V_1$  is the voltage at non-inverting input of the Opamp and  $V_3$  is the voltage at the output of the Opamp[4][7]. Output current has been calculated after determining the voltages the and finally given by Equation (4). Transconductance gain has also been calculated by the parameter  $(I_o/V_i)$  considering  $V_{out}$  grounded[8]. Similarly the output impedance  $Z_o$  is calculated by  $(I_o/V_o)$  with  $V_i$  grounded.

$$\frac{V_1}{R_1} + \frac{V_i - V_0}{R_5} + \frac{V_1 - V_2}{Z_i} = 0 \quad (1)$$

$$\frac{V_2 - V_1}{Z_i} + \frac{V_2 - V_3}{R_3} + \frac{V_2 - V_i}{R_2} = 0 \quad (2)$$

$$\frac{V_3 - V_0}{R_4} + \frac{V_3 - V_2}{R_3} + \frac{V_3 - (V_1 - V_2)}{R_0} = 0 \quad (3)$$

$$\frac{V_3 - V_0}{R_4} + \frac{V_1 - V_0}{R_5} = I_o \quad (4)$$

$$A(s) = \frac{A_0}{1 + s/\omega_{c0}} \quad (5)$$

Where,  $A_0$  are the open-loop gain at zero frequency and  $\omega_{c0}$  is the open-loop gain corner frequency.  $Z_i$  can also be determined using above equations and given below.

$$Z_i(s) = \frac{1}{1/R_1 + sC_{in}} \quad (6)$$

The shunt impedance ( $Z_s$ ) of the circuit is calculated by applying Norton theorem in figure1 and the trans conductance gain of the amplifier ( $G_M$ ) has been calculated by the above equations and given below.

$$Z_s = -I_o/V_0 \quad \text{where } V_i = 0 \quad (7)$$

$$G_M = I_o/V_i \quad \text{where } V_0 = 0 \quad (8)$$

### IV. METHOD FOR OBTAINING TRANSFER FUNCTION BASED ON CLASSICAL FEEDBACK THEORY

In classical feedback theory, the approach uses to find transfer function of a system in which the Op-amp circuit is taken in terms of its corresponding closed-loop gain is discussed in this section. The equivalent transfer

functions are obtained by means of superposition[7][9]. Then, all the blocks are reduced into a single transfer function by means of the simplification formula given below

$$T.F=P(s).G(s)/(1+G(s)H(s)) \tag{9}$$

This approach ignores the non-linear characteristics of the opamp like slew rate. In Figure 2,we are considering the setup shown where a very small sinusoidal signal is applied at the non-inverting input. Since the output is proportional to the input, the output is also sinusoidal.It is very clear that if the Op-amp becomes saturated, the output would no longer look like a sinusoidal signal[5][6]. Within the desired frequency range,the experimental data is obtained by taking the ratio of the output to the input sinusoid, at different frequencies. These ratios are then plotted in Bode plot format to obtain something similar to what is shown at the bottom of Figure 2. The open-loop gain is considered  $G_0$  and Corner frequency is  $\omega_0$ . The Op amp, operated in open-loop mode as follow.

$$\frac{G_0}{1+s/\omega_0} \tag{10}$$

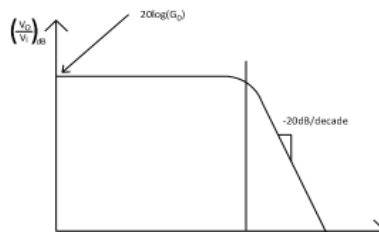


Figure 2: Open-loop testing of an Op-amp

Here figure 3 depicted below represents the block diagram to find the transfer function of a system related with op amp circuit.

$$P(s) = \frac{G(s)}{1+G(s)H(s)} \tag{11}$$

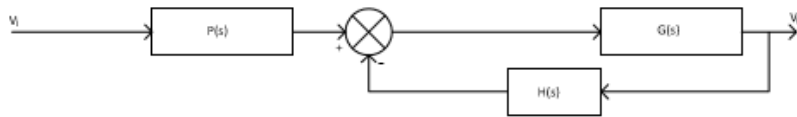
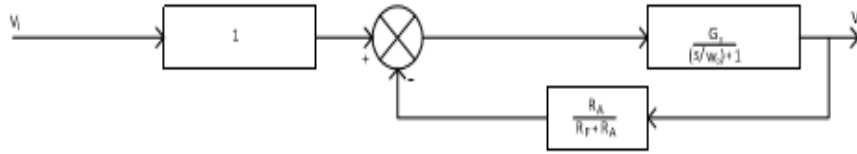


Figure 3: Transfer function determining block diagram

Here a inverting and non-inverting op amp amplifier are used for an example to find the transfer function using above model. It is important to translate a resistor bridge circuit into a transfer function. For instance, consider how the output is ‘feedback’ to input via the resistor bridge, composed of  $R_F$  (Feedback resistance)and  $R_A$  (Resistance connected with inverting terminal). To obtain this transfer function, the superposition theorem has been used, which allows us to investigate the contribution of individual signals, one at a time. Non inverting amplifier is taken first to find the transfer function. Here the input is  $V_o$  and the input is  $V_i$  .The resulting transfer function is given below.

$$\frac{V_i}{V_o} = \frac{R_A}{R_F + R_A} \tag{12}$$

Again  $G(s)$  is the Op-amps transfer function has been calculated in the previous section and given in equation(10).  $P(s)$  is very simple and it is equal to 1 as the complete input signal reaches the input terminal.Now we can use the classical feedback control equation to simplify this collection of blocks into a single transfer function as follows,



**Figure 4: Block diagram representation of non-inverting opamp**

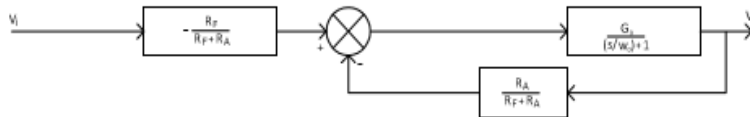
From the above block diagram, the transfer function for non-inverting opamp is given below.

$$\frac{V_0}{V_i} = 1 * \frac{\frac{G_0}{1+s/\omega_0}}{1 + \frac{G_0}{1+s/\omega_0} * \frac{R_A}{R_F+R_A}} \quad (13)$$

Similarly for inverting opamp, P(s) has to be changed as the input signal goes first into a resistor bridge. It is also considered that the input impedance of the Op amp is infinite and its output impedance is zero. Also notice that the input has an effect on the inverting side. The corresponding transfer function for P(s) is given below.

$$P(s) = - \frac{R_F}{R_F+R_A} \quad (14)$$

Again applying classical feedback control equation to simplify this collection of blocks into a single transfer function as follows,



**Figure 5: Block diagram representation of inverting opamp**

From the above block diagram, the transfer function for non-inverting opamp is given below.

$$\frac{V_0}{V_i} = - \frac{R_F}{R_F+R_A} \frac{G_0}{(1+s/\omega_0) + G_0 \frac{R_A}{R_F+R_A}} \quad (15)$$

## V. TRANSFER FUNCTION OF HOWLAND CURRENT SOURCE

Now the transfer function of Howland current source is to be found out which is our main intention in this work. As this current source is linear only in transient section, we can improve its only transient response which will be beneficial for electrical stimulation causes fast flow of charge from the source. If any device goes into saturation (steady state) quickly is called relatively more stable. Applying the approach stated above in figure (1), the transfer function can be written as follows.

$$T.F = - \left( \frac{R_5}{R_1+R_5} \right) \left[ \frac{\frac{G_0}{1+s/\omega_0}}{1 + \frac{G_0}{1+s/\omega_0} * \frac{R_5}{R_1+R_5}} \right] + \left( \frac{R_L}{R_3+(R_L \parallel R_3)} \right) \left[ \frac{\frac{G_0}{1+s/\omega_0}}{1 + \frac{G_0}{1+s/\omega_0} * \frac{R_L}{R_3+(R_L \parallel R_3)}} \right] \quad (16)$$

The above equation can be rearranged and given below.

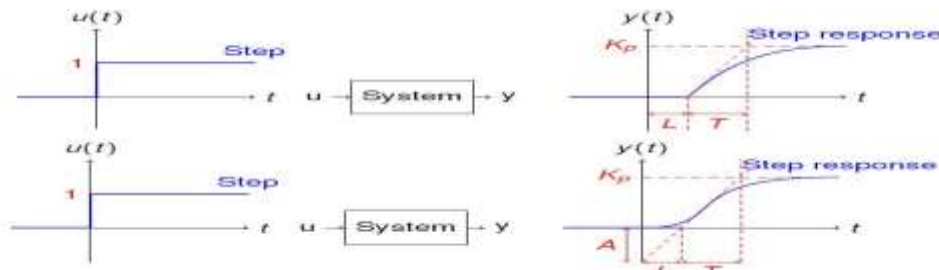
$$T.F = \frac{K}{K_1 S^3 + K_2 S^2 + K_3 S + K_0} \quad (17)$$

Where  $K_1$  is the function of  $(R_1, R_5)$

$K_2$  is the function of  $(R_1, R_2, R_5)$   
 $K_3$  is the function of  $(R_2, R_3, R_5)$   
 $K_0$  is the function of  $(R_1, R_2, R_3, R_5)$   
 $K$  is the function of  $(\omega_0, G_0)$

**VI. PID CONTROLLER TUNING METHOD**

Control System and designing of controller has nowadays been one of the most important parts of development in the field of technology as well as research. It plays an important role for the advancement of modern civilization as well. PID controllers are the most important and popular controller used in field of research. The rule to tune the PID Controller had proposed by Ziegler and Nichols in the year of 1942. They use the tangent method to determine the parameter. The proper tuning and efficient methods of the PID controller controls the different parameter s of the plant. The proper tuning of the controller using the proper parameter values can give an expected and better experimental result to enhance the performance of the system. The Z-N step response method which was introduced in the year of 1942 is the best classical tuning method for PID controllers[13][14][15]. The step response method which is the best classical tuning method for PID controllers are basically based on an open loop step response method which requires the system to be stable. It has been observed that the unit step response of a process mainly depends on two parameters L & T. These two parameters can be calculated by drawing a tangent line at the inflexion point where the slope of the step response can have its maximum value. The process parameters have been shown in Fig1.



**Fig 6: Response Curve for Ziegler-Nichols Tuning Rule**

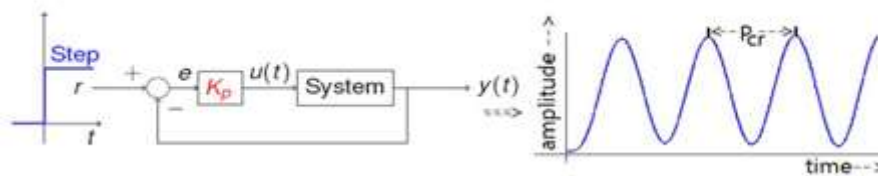
The different parameter values of P, PI and PID controllers obtained from the Ziegler-Nichols open loop step response method has been shown below in Table 1.

Controller Type	$K_p$	$T_i$	$T_d$
P	$T/L$		
PI	$0.9 T/L$	$L/0.3$	
PID	$. 1.2 T/L$	$2L$	$0.5L$

**Table1: Parameter values from Z-N Step Response Method**

The procedure for Sustain Oscillation in a Closed Loop Method is as follows: -

- Proportional Control ( $k_p$ ) has been selected alone[15][16].
- The value of  $k_p$  has been increased until point of stability and the critical gain  $K_{cr}$  has been reached.
- The period of oscillation has been calculated to obtain the time constant  $P_{cr}$ .
- The PID parameters can be calculated using values of  $K_{cr}, P_{cr}$ .



**Fig 7: Closed Loop Method for Ziegler-Nichols Tuning**

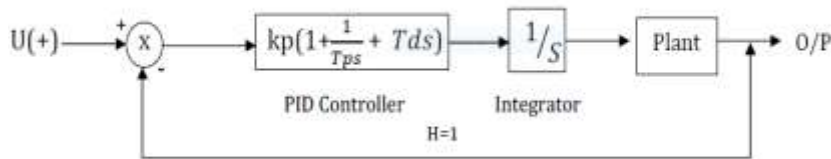
Different parameter values of P, PI, PID controller observed from Z-N tuning closed loop method shown below.

Controller Type	Kp	Ti	Td
P	0.5 Kcr		
PI	.45Kcr	1/1.2 Pcr	
PID	.6Kcr	0.5Pcr	.125Pcr

**Table2: Parameter values from Z-N Sustain Oscillation Method**

**VII. ADDITION OF POLE TO A SYSTEM**

Addition of pole to a linear time invariant system has the effect of pulling the root locus to the right (jω axis) making the system less stable. The response of a system can be determined by the location of pole. Though addition of pole makes a system less stable it is required for a system to increase the type of the system which reduces the steady state error. Except first order system all other system exhibits' oscillation. As addition of pole at origin to a system increases order of the system, oscillation increases and makes the output towards undesired value. In this work, derived transfer function of Howland current source is connected with an integrator to provide a pole at origin. Then a proper PID controller has been designed in the next section. Here plant is nothing but our Howland current source.



**Fig 8: The block diagram or proposed design**

**VIII. OUR PROPOSED DESIGN AND PID CONTROLLER**

In this section the tuning parameter of PID controller has been calculated by using Z-N tuning rule to get the optimum performance of the Howland current source. Initially it is considered that  $Ti = \infty, Td = 0$ . Here we consider some typical values of resistance which is generally used for Howland current source. After that passing through an integrator, now the equation (17) is changed into a mathematical form and shown below.

$$\frac{1}{264s^3 + 5280s^2 + s^1} \tag{18}$$

Again the gain of PID Controller is  $Kp$ . The closed loop Transfer Function of system and different parameters of the controller has been calculated from equation (18) as follows.

$$\frac{C(s)}{R(s)} = \frac{Kp}{264s^3 + 5280s^2 + s^1 + Kp} \tag{19}$$

Characteristic Polynomial can be obtained from equation can be written as follows.

$$q(s) = 264s^3 + 5280s^2 + s^1 + Kp \tag{20}$$

The value of  $Kp$  is responsible for making the system marginally stable. So the sustain oscillation occurrence can be obtained by Routh criterion.

$s^3$	264	1	0
$s^2$	5280	$Kp$	0
$s^1$	$\frac{5280 - 264Kp}{5280}$	0	0
$s^0$	$Kp$	.	.

To find the critical gain ( $Kcr$ ) of the system the  $s^1$  row is made zero.

Thus  $\frac{5280 - 264 Kp}{5280} = 0$

From equation (4) the value of has been calculated as  $Kp = 20$

$Kp = Kcr = \text{critical gain} = 20$

The auxiliary equation can be written from the R-H array as.

$$5280s^2 + K_p = 0 \quad (21)$$

Putting the value of  $K_p = 20$  in equation(5) we get ,  $5280s^2 + 20 = 0$

$$s^2 = -\frac{20}{5280} = -0.0037$$

As it is known  $s = j\omega$  , the equation can be replaced with the value of  $s$ . So the equation becomes  $(j\omega)^2 = -0.0037$   
 $-\omega^2 = -0.0037$  .

$$\omega = 0.6.$$

This  $\omega$  is called  $\omega_{cr}$ .

$$\text{Now calculating } P_{cr} = \frac{2\pi}{\omega_{cr}} = \frac{2\pi}{0.06} = 105$$

According to Z-N tuning rule we can calculate the value of  $K_p$ ,  $T_i$ ,  $T_d$  using the values of  $K_{cr}$  &  $P_{cr}$ .

$$K_p = 0.6 K_{cr} = 20 * 0.6 = 12 \quad (22)$$

$$T_i = 0.5 P_{cr} = 0.5 * 105 = 53 \quad (23)$$

$$T_d = .125 P_{cr} = .125 * 105 = 13 \quad (24)$$

As the value of  $K_p$ ,  $T_i$ ,  $T_d$  has been calculated, the transfer function of the PID controller can also be calculated using as

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

$$= 12 \left( 1 + 13s + \frac{1}{53s} \right) = 12 \left( \frac{689s^2 + 53s + 1}{53s} \right) \quad (25)$$

The transfer function of proposed modified system model of cardiac muscle is given by.

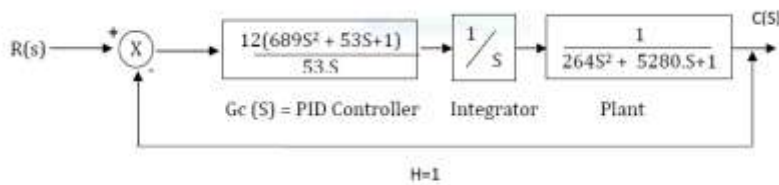


Fig 8: The control system based modeling of Howland current source with PID controller

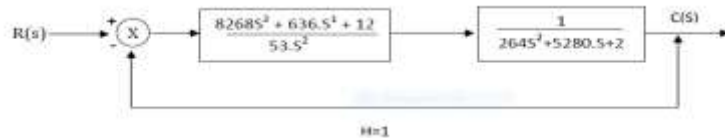


Fig 9: The Reduced block diagram of Plant with PID controller

Now the closed loop transfer function of the system is shown below.

$$\frac{G}{1+G} = \frac{5040s^2 + 315s^1 + 5}{18711s^4 + 162036s^3 + 51035s^2 + 315s^1 + 5} \quad (26)$$

### IX. SIMULATION RESULT

The simulation result is depicted in this section considering the step response of Howland current source without controller and integrator. Here the system has been simulated in MATLAB software and is given in the figure below.

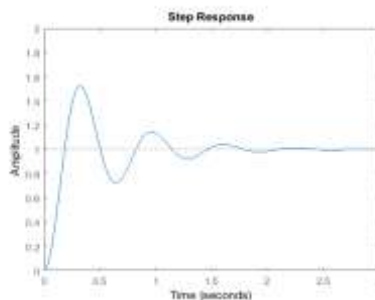


Fig10: Step Response of Plant without controller and integrator

The step response of the plant(Howland current source) with Z-N tuned PID controller and integrator has also been simulated and is given in the figure below.

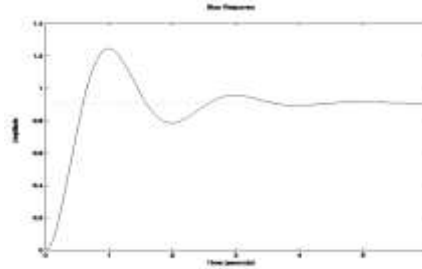


Fig 11: Step Response of plant with PID Controller in with series with an integrator

## X. COMPARATIVE STUDY OF SIMULATION RESULTS

In this work the step response of plant (Howland current source) followed by an integrator and proper designed PID tuned controller has been simulated above in MATLAB 13.0 software. It has been observed that the Rise time and the Settling time are significantly reduced under PID controller along with an integrator. As less settling time gives more stability for a system, it can be concluded that our proposed design gives more stability.

## XI. CONCLUSION

In this paper the Z-N tuning rule with PID controller has successfully been applied to design a proper PID controller for the improvement of system response of Howland current source after finding the transfer function in classical feedback approach. Addition of pole at the origin has taken into account to avoid any disturbances the steady state part of the plant. A comparative study using simulation result has also been depicted in this work. Finally our proposed model increases the speed of the system as transient response improves which leads the electrical stimulation faster.

## RERERANCES

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