ANALOG FABRICATION OF PID CONTROLLER

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Bachelor of Technology in Electrical Engineering

By

Tapan Kumar Swain
Vaibhav Baid

Under supervision of
Prof. Sandip Ghosh

Department of Electrical Engineering
National Institute of Technology, Rourkela
May 2014

CERTIFICATE

This is to certify that the project entitled, "**Analog fabrication of PID Controller**" submitted by **Tapan Kumar Swain and Vaibhav Baid** is an authentic work carried out by them under my supervision and guidance for the partial fulfillment of the requirements for the award of **End semester thesis Submission** in **Electrical Engineering** at **National Institute of Technology, Rourkela (Deemed University).**

Prof. Sandip Ghosh

Rourkela Dept. of Electrical Engineering,

National Institute of Technology,

Rourkela,

Orissa-769008

ABSTRACT

The PID controller has been used and dominated the process control industries for a long time as it provides the control action in terms of compensation based on present error input(proportional control), on past error(integral control) and on future error if recorded by earlier experience or some means(derivative control). The PID controllers have excellent property of making the system response faster and at the same time reduce the steady state error to zero or at least to a very small tolerance limit. The work below starts with study of individual components of the controller and their responses in a certain environment for different test signals (say a step or sine wave input).The problem is to design a PID controller using appropriate analog circuit as well as understand and utilize the advantages of all the three terms. The below work is for the study of an analog PID controller using operational amplifiers and fabricate the controller on hardware after testing the individual terms:-proportional, integral and derivative.

ACKNOWLEDGEMENT

We express our gratitude and sincere thanks to our supervisor Prof. Sandip Ghosh, Professor Department of Electrical Engineering for his constant motivation and support during the course of our thesis. We truly appreciate and value his esteemed guidance and encouragement from the beginning of our thesis. We are indebted to him for having helped me shape the problem and providing insights towards the solution.

We, Tapan Kumar Swain and Vaibhav Baid, are thankful to each other for co-operating and encouraging and being alongside for the literature review and background study, the hardware implementation, experiments and the whole thesis in the same project work.

We extend our gratitude to the researchers and scholars whose hours of toil have produced the papers and thesis that we have utilized in our project.

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INTRODUCTION

Looking back to the history of the PID controller, the PID controllers in the initial days were all pneumatic. In fact, the experimentations were carried out all with pneumatic controllers by Ziegler and Nichols. But the nature of pneumatic controllers was slow. The electronic controllers started replacing the conventional pneumatic controllers after the development of electronic devices and operational amplifiers. However, with the advent of the microprocessors and microcontrollers, the implementation with digital PID controllers has now become the main focus of development. The topmost benefit of using digital PID controllers is that the controllers' parameters can be programmed effortlessly; consequently, without changing any hardware, they can be changed. Furthermore, besides generating the control action, the same digital computer can be used for a number of other applications.

But here we are concerned with the analog PID controller design, and how they can be implemented in actual practice. The design of automatic control systems is perhaps the most important function that the control engineer carries out. We may analyze and find out methods to do the design in certain cases while mostly we do design based on trial and error basis. This requires that we should put some restrictions and constraints along with pre-specified performance conditions in order to get a better quality control in terms of performance. So, design requires various factors to be taken care of.

Every control system designed for a specification or specific application has to meet certain performance specifications. Some methods specifying the performance of a control system are:-

1. By set of specifications in time domain and/or in frequency domain such as peak overshoot, settling time, gain margin, phase margin, steady-state error etc.
2. By optimality of a certain function, e.g., an integral function.

In addition to performance specification, some other constraints are also always imposed on the control system design. Say for example, the tracking antenna control system where an actuator is designed for movement of antenna. Depending on required performance, power supply available, space and economic limitations etc., it could be servomotor (ac or dc) or hydraulic motor. Size is determined by inertia, velocity and acceleration ranges of antenna. Gear trains for higher speeds may be required.

From this discussion, it is evident that the choice of plant components is dictated not only by performance but also size, weight, available power supply, cost etc. Therefore, the plant generally cannot meet the performance specifications. Though the designer is free to choose alternative components, this is generally not done because of cost, availability and other constraints.

However, some components of a plant, its replacement are not a big problem because of low- cost and wide- range of availability of such amplifiers. Merely by gain adjustments, it may be possible to meet the given specifications on performance of simple control systems. In such cases, gain adjustment seems to be the most direct and simple way of design. However, in most practical cases, the gain adjustment does not provide the desired result. As it is usually the case, increasing the gain reduces the steady-state error but results in oscillatory transient response or even instability. Under such circumstances, it is necessary to introduce some kind of corrective subsystems to force the chosen plant to meet the specifications. These subsystems are known as controllers/compensators and their job is to compensate for the deficiency in the performance of the plant.

There are basically two approaches to control system design problem:-

1. We select the configuration of the overall system by introducing controller and then choose the performance parameters of the controller to meet the given specifications on performance.
2. For a given plant, we find overall system that meets the given specification and then compute the necessary controller.

   The first approach will be used below in the work.

So, we find that plant components are determined considering various factors and plant cannot meet these specifications. For this gain adjustment seems suitable, as replacing by alternative components may be costly or impractical. This is because the steady state error transfer function is inversely proportional to open loop gain and is given by:-

$$\frac{E(s)}{R(s)} = \frac{1}{1+G(s)} \tag{1}$$

Where

G(s) = open loop transfer function or gain

However gain adjustment using such Proportional gain (P) leads to oscillatory transient response and may lead to instability, although it reduces steady state error to some extent.

So, we use a PID controller which can have the advantage of making the system response faster, reduce the steady state error to zero or within a desirable tolerance limit. The use of PID controller, however, is avoided in some process industries now-a-days and they prefer PI controller because the derivate control poses some problems. Here we study each of the control parameters viz., proportional, integral, derivative individually or with combination as PD or PI and then we can fabricate a PID controller on hardware for an arbitrary plant using appropriate tuning techniques and meanwhile understand the advantages that can be more prominent and utilized for a particular specification. The fundamental difficulty with PID control is that it is a feedback system, with constant parameters, and no direct knowledge of the process, and thus overall performance is reactive and a compromise. While PID control is the best controller in an observer without a model of the process, better performance can be obtained by overtly modeling the actor of the process without resorting to an observer.

PID controllers, when used alone, can give poor performance when the PID loop gains must be reduced so that the control system does not overshoot, oscillate or hunt about the control set point value. They also have difficulties in the presence of non-linearities, may trade-off regulation versus response time, do not react to changing process behavior, and have lag in responding to large disturbances.

The most significant improvement is to incorporate feed-forward control with knowledge about the system, and using the PID only to control error. Alternatively, PIDs can be modified in more minor ways, such as by changing the parameters, improving measurement, or cascading multiple PID controllers.

Another problem faced with PID controllers is that they are linear, and in particular symmetric. Thus, performance of PID controllers in non-linear systems is variable. For example, in temperature control, a common use case is active heating but passive cooling, so overshoot can only be corrected slowly – it cannot be forced downward. In this case the PID should be tuned to be over damped, to prevent or reduce overshoot, though this reduces performance (it increases settling time).

A problem with the derivative term is that it amplifies higher frequency measurement or process noise that can cause large amounts of change in the output. It does this so much, that a physical controller cannot have a true derivative term, but only an approximation with limited bandwidth. It is often helpful to filter the measurements with a low-pass-filter in order to remove higher-frequency noise components. As low-pass filtering and derivative control can cancel each other out, the amount of filtering is limited. So low noise instrumentation can be important. A nonlinear median filter may be used, which improves the filtering efficiency and practical performance. In some cases, the differential band can be turned off with little loss of control. This is equivalent to using the PID controller as a PI controller.

BACKGROUND AND LITERATURE REVIEW

A **proportional-integral-derivative controller** (**PID controller**) is one of the widely used controllers in industries for controlling feedback systems. PID controller calculates an error value also called actuating signal which is the difference between a measured process variable or the output value and a desired value or set point input. The error is controlled or reduced by manipulating /adjusting the inputs that the PID controller receives and thus it produces a command signal to the plant for error correction.

The error correction is done for a control system in 3 ways basically viz., proportional, integral and derivative. A controller can use either of these term or their combinations, however, integral and derivative control are achieved along with proportional control. PID controller is the one which has all the three terms in it. So, three separate constant parameters are calculated and hence it is also called a **three-term control.** In time domain this may be interpreted as: *P* depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on present rate of change. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve, a damper, or the power supplied to a heating element.

In the absence of knowledge of the underlying process, a PID controller has historically been considered to be the best controller. By tuning the three parameters in the PID controller, the controller can provide control action desired for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point, and the degree of system oscillation. However, we should understand that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability.

Some applications may require using only one or two actions to provide the appropriate system control. This is achieved by setting the other parameters to zero. A PID controller will be called a PI, PD, P or I controller in the absence of the respective control actions. PI controllers are fairly common, since derivative action is sensitive to measurement noise, whereas the absence of an integral term may prevent the system from reaching its target value due to the control action.

PID CONTROL

The PID control scheme is named after its three correcting terms, whose sum constitutes the manipulated variable (MV). The proportional, integral, and derivative terms are summed to calculate the output of the PID controller. Defining U(t) as the controller output, the final form of the PID algorithm is given by:

$$\mathrm{U(t)} = \mathrm{MV(t)} = k_p\, e(t) + k_i \int_0^t e(k)dk + k_d \frac{de(t)}{dt} \tag{2}$$

Where

k_p: Proportional gain, a tuning parameter

k_i: Integral gain, a tuning parameter

k_d: Derivative gain, a tuning parameter

e: Error, (Set point- output value)

t: Time or instantaneous time (the present)

k: Variable of integration; takes on values from time 0 to the present t

The general block diagram for a PID controller is shown below in fig1

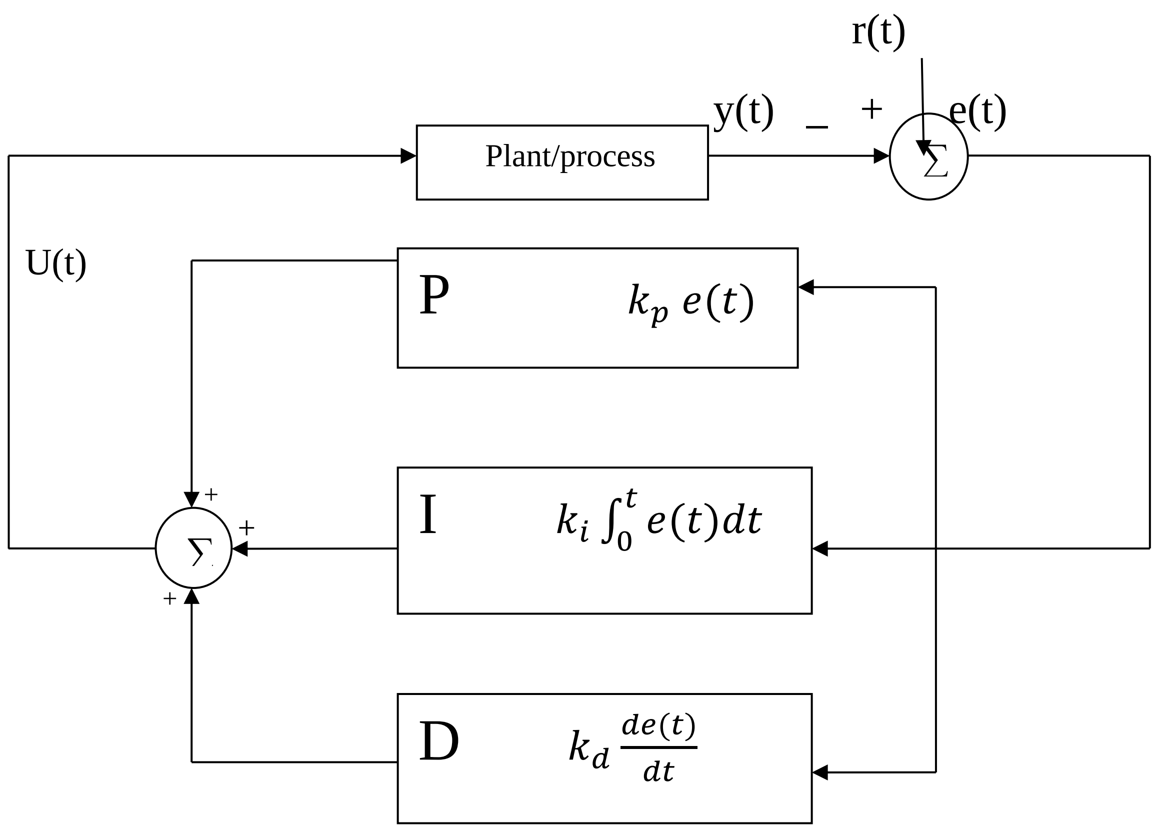

Fig 1- block diagram of a PID controller

The above block diagram and equation shows the PID controller behavior in time domain form. The time domain analysis is used for real-time results and to determine various gain parameters like rise time, peak overshoot, steady-state error etc. However, there is another form of representation that helps in determining the performance parameters like stability, gain and phase margins etc. This form is given below.

TRANSFER FUNCTION REPRESENTATION

Sometimes it is useful to write the PID control equation in Laplace transform form which is given by:

$$G(s) = k_p + \frac{k_i}{s} + k_d s = \frac{k_d s^2 + k_p s + k_i}{s} \tag{3}$$

$\boldsymbol{k_p, \ k_d \ and \ k_i}$ are the proportional, derivative and integral gain respectively. This transfer function can be realised using various RLC circuits, opamp circuits etc. This function is in frequency domain thus, being used for frequency domain analysis. As we can see from the transfer function, it has one pole at s=0 i.e. origin and two zeros. The addition of a pole to the system and that too on the imaginary axis makes the system sluggish. This form is helpful in designing a controller based on stability criteria where we may be having bode plot of the system, or its root locus diagram, by using various tuning techniques.

ANALOG PID IMPLEMENTATION

For implementing the PID controller we can use both digital and/or analog circuits. Digital PID is implemented using integrated circuits while we can use various circuits using operational amplifiers in case of analog design of which one is shown in fig 3.

From fig 3, we see that it is basically three different inverter circuits with different values of impedances $Z_f(s)$ and $Z_i(s)$. The inverter circuit is shown in fig 2.

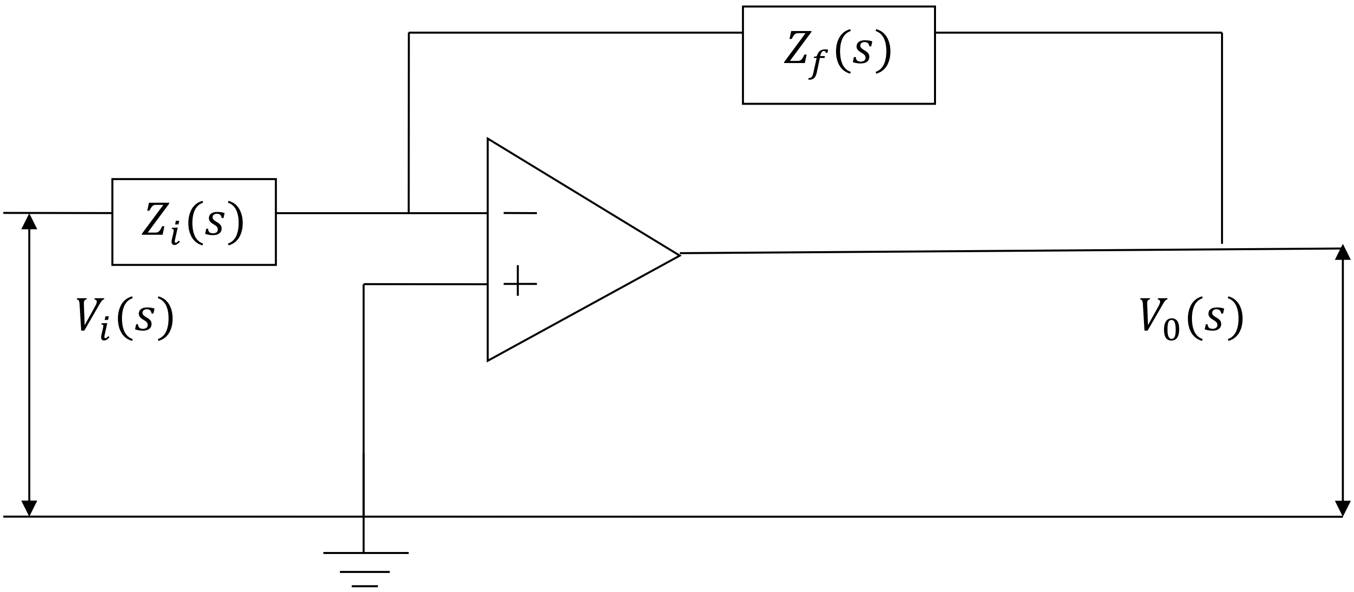

Fig 2- an inverter circuit

The above inverter circuit has a closed loop gain given by:-

$$G(s) = -\frac{Z_f(s)}{Z_i(s)} \qquad (4)$$

For different values of $Z_f(s)$ and $Z_i(s)$, we can get various control actions and thus implement different types of controllers as shown in Table[1].

Table 1:-

controller	$\boldsymbol{Z_f}$	$\boldsymbol{Z_i}$	**Transfer Function G(s)**
P	R_f	R_i	$-\frac{R_f}{R_i}$
PI	$R_f + \frac{1}{sC_f}$	R_i	$-[\frac{R_f}{R_i} + \frac{1}{sC_f R_i}]$
PD	R_f	$\frac{R_i}{sC_i R_i + 1}$	$-[\frac{R_f}{R_i}(sC_i R_i + 1)]$
PID	$R_f + \frac{1}{sC_f}$	$\frac{R_i}{sC_i R_i + 1}$	$[\frac{-(sC_i R_i + 1)(sC_f R_f + 1)}{sC_f R_i}]$

Transfer function of various controllers using Op Amps

So, the transfer functions using Op Amp for PID controller can be as in Table [1] is

$$G(s) = -\frac{(sC_i R_i+1)(sC_f R_f+1)}{sC_f R_i} \tag{5}$$

Or,

The transfer function can take following shape as per the diagram

Shown in fig3 as follows:

$$G(s) = -\left[\frac{R_{P2}}{R_{P1}} + \frac{sC_D R_D}{sC_D R_C+1} + \frac{1}{sC_I R_I}\right] \tag{6}$$

This circuit contains a summer circuit that sums up command signal generated by each of the control terms and finally an inverter is used for getting positive value of transfer function.

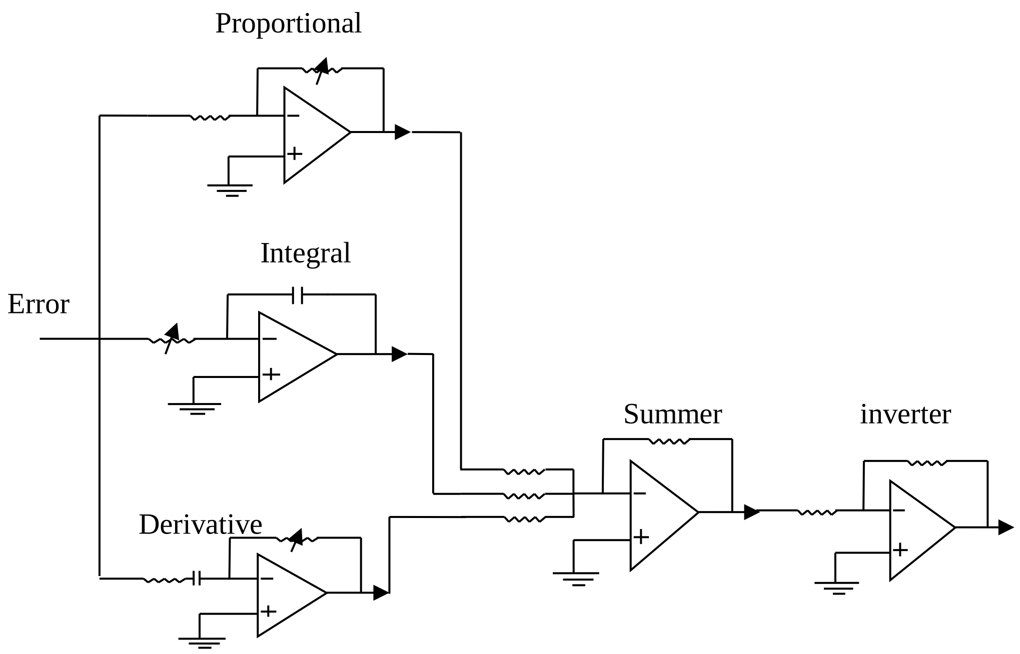

Fig 3-Circuit diagram of a PID controller

EFFECTS OF GAIN PARAMETERS ON PERFORMANCE

Let us consider a second order system. The overall transfer function for a closed loop second order system can be written in standard form as:

$$\frac{C(s)}{R(s)} = \frac{{w_n}^2}{s^2+2\Im w_n+{w_n}^2} \tag{7}$$

The study of second order systems is important because it is simpler and higher order systems can be approximated to a fair extent by second order systems and thus, one can get fair idea about the dynamics of the system and steady state error. The dynamics refers to the response of a system response to an abnormal condition such as lightning, sudden rise of voltage, constantly increasing input etc., and such systems are studied using test signals like impulse, step, ramp etc.

The dynamics can be analyzed by knowing the damping ($\Im$) and undamped natural frequency (w_n).This can give known from the system response viz., peak overshoot (M_p), rise time (t_r), settling time (t_s), steady-state error (e_{ss}).

For a step input, these values are given by following equations:-

1. Rise time (t_r) is the time required by response to rise from 10% to 90% of final value for overdamped system and 0 to 100% for underdamped system.

$$t_r = \frac{\pi - tan^{-1}\frac{\sqrt{1-\Im^2}}{\Im}}{w_n\sqrt{1-\Im^2}} \tag{8}$$

2. Peak overshoot(M_p), is normalized difference between peak of response and steady state output normalized w.r.t. to steady output.

$$M_p = e^{-\frac{\pi\Im}{\sqrt{1-\Im^2}}} \tag{9}$$

3. Settling time (t_s) is the time required for the response to reach and stay within specified limit of its final value called tolerance band (2-5%).This value is for 5% band,

$$t_s = \frac{4}{\Im w_n} \tag{10}$$

4. Steady state error(e_{ss}) is the error between the actual output and desired output as t tends to infinity.

$$e_{ss} = \frac{2\Im}{w_n} \tag{11}$$

By introduction of PID controller we can control these above system dynamics using tuning methods and thus determine various parameters. The effects of these parameters on system response are shown in table below.

We can see that with increase in the value of k_p , we get better steady state stability as it reduces the steady-state error. The integral control can nullify the steady state error but cost paid is that it makes the system sluggish. While above two lead to oscillatory response initially, the derivative control makes the overshoot within limit and also improves the settling time.

Table 2:-

Parameter	Rise time	Overshoot	Settling time	Steady-state error	Stability
k_p	Decrease	Increase	Small change	Decrease	Degrade
k_i	Decrease	Increase	Increase	Eliminate	Degrade
k_d	Minor change	Decrease	Decrease	No effect in theory	Improve if k_d is small

Effects of increasing control parameter independently

Table [2] shows how change in various gain parameters affects the response of the system both transient and steady state.

THE 741 OPAMP

The OPAMP stands for operational amplifier. The opAmp is an amplifier with some specific important characteristics. As the word amplifier suggests, the function of an operational amplifier (op amp) is to amplify a voltage. However, the operational amplifier does much more than that. It also functions as a buffer and as a cascade which are two functions that enable simple circuits to be assembled into complex circuits to create higher level functions which are called operations¾ hence the name operational amplifier.

Op amps have five terminals that are important. The voltage that is amplified is the difference between the voltage at the '+' terminal $V_p$and the voltage at the '-' terminal V_n, as shown in figure below. The amplified voltage is the output voltage V_o. Unlike the resistor and capacitor, which are both "passive" (unpowered) devices, the opamp is an "active" device. Indeed, the op amp needs a voltage supply for the amplification. The V_s^+ and the V_s^- terminals are the positive and negative supply voltages, respectively. The op amp schematic and the chip that we'll use are shown in figure below. Generally it is available in integrated chips. The pin configuration of 741 IC is as shown below.

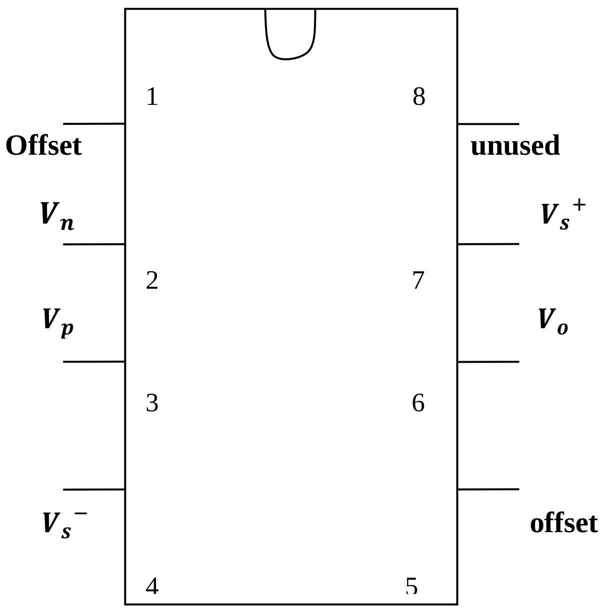

Fig 4- Pin configuration of 741 opamp

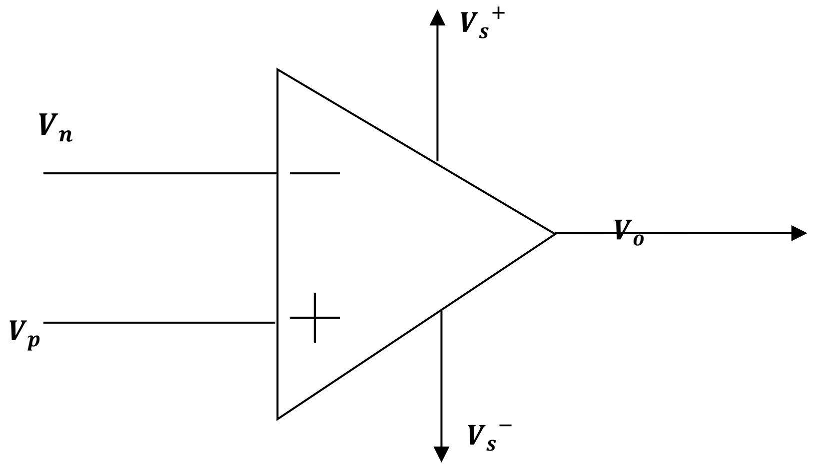

Fig 5- Circuit symbol of an opamp

DATASHEET FOR LM741

Absolute maximum Ratings

TABLE 3:-

	LM741A	LM741	LM741C
Supply Voltage	±22V	±22V	±18V
Power Dissipation	500 mW	500 mW	500 mW
Differential Input Voltage	±30V	±30V	±30V
Input Voltage	±15V	±15V	±15V
Output Short Circuit Duration	Continuous	Continuous	Continuous
Operating	−55°C to +125°C	−55°C to +125°C	−55°C to +125°C

Temperature Range			
Storage Temperature Range	−65°C to +150°C	−65°C to +150°C	−65°C to +150°C

Datasheet for 741 IC

"Absolute Maximum Ratings "indicate the limits beyond which damage to the device may occur. Operating Ratings indicate the conditions for which the device is functional, but do not ensure specific performance limits. For operation at elevated temperatures, these devices must be derated based on thermal resistance.

For supply voltages less than ±15V, the absolute maximum input voltage is equal to supply voltage.

OPAMP REALISATIONS

SIGNAL BUFFER:-

It is a circuit configuration in which input equals output. The importance of this circuit is that it isolates the input and output side. Since, the input current of opAmp is 0, loading effect is 0. So, we can measure the actual input without error due to loading. Its circuit diagram is shown below.

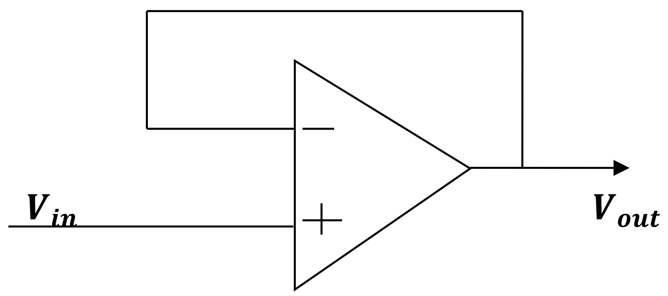

Fig 6- signal buffer circuit

SIGNAL INVERTER:-

This circuit changes the polarity of the input signal with amplification and the gain value is,

$$Gain = -\frac{R_2}{R_1} \tag{12}$$

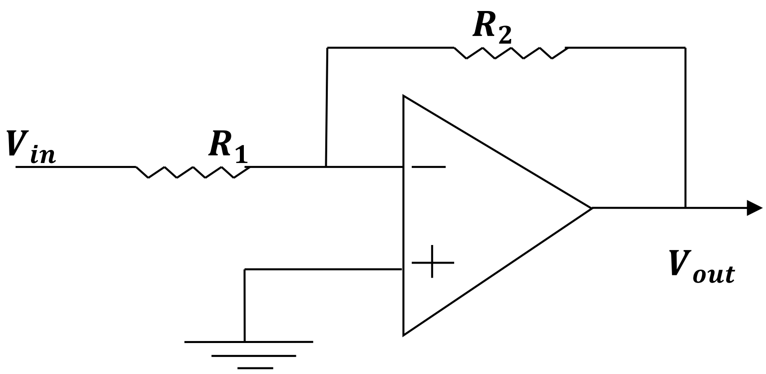

Fig7- signal inverter circuit

SIGNAL ADDER/SUMMER:-

This circuit helps in summing up various signals .Here, output voltage is given by

$$V_{out} = V_{in1} + V_{in2} + V_{in3} \tag{13}$$

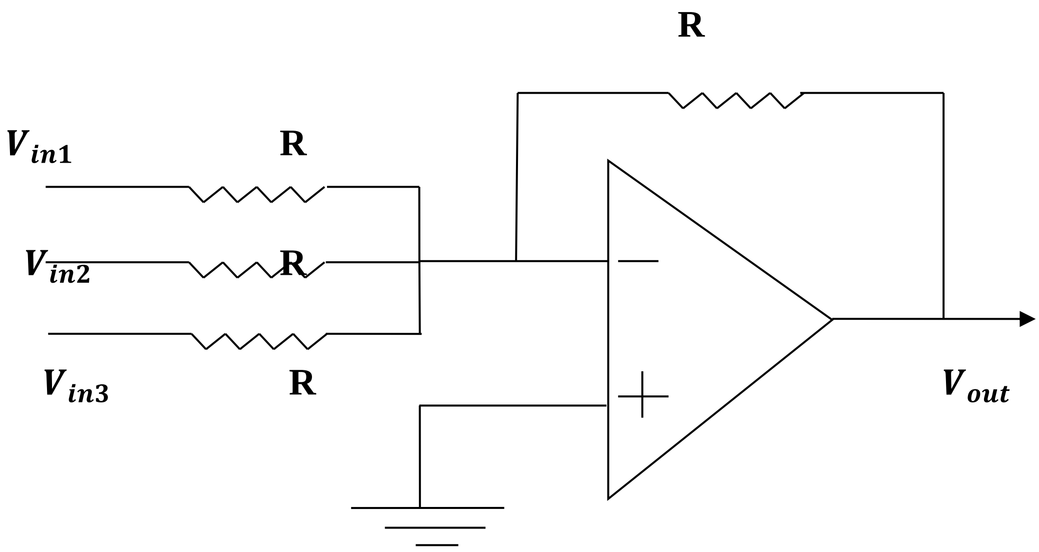

Fig 8- signal summer circuit

SIGNAL SUBTRACTOR/DIFFERENTIATOR:-

This circuit gives the difference of the two inputs given to the opamp circuit, provided all the resistances should have same value as shown in the circuit below. Here output signal is given as

$$V_{out} = V_{in1} - V_{in2} \tag{14}$$

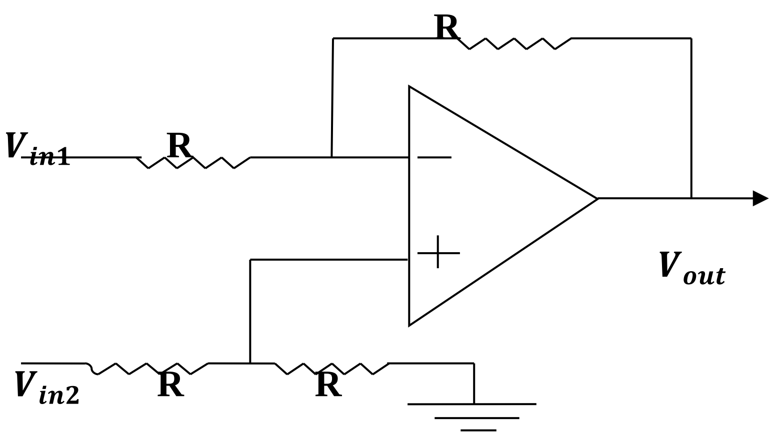

Fig 9- signal differentiator circuit

CHOICE OF CIRCUIT PARAMETERS

We need to initially determine the values of k_p, k_d and k_i for a certain PID controller. Since our plant is unknown we assume our plant to be anything arbitrary and thus our controller should be tunable one.

We need a PID controller for 0<=k_p <=100, 0<=k_d <=10 and an arbitrary k_i as per requirement.

Firstly, we need to test each components of the controller viz., proportional, integral and derivative terms separately and then integrate them together. So, we assemble the components for the proportional controller. As 0<=k_p <=100, we chose our $R_2 = 100k$ pot and $R_1 = 1k$ ohms. We chose a 741 opAmp for this purpose. Initially, we set up the board as shown in circuit diagram below.

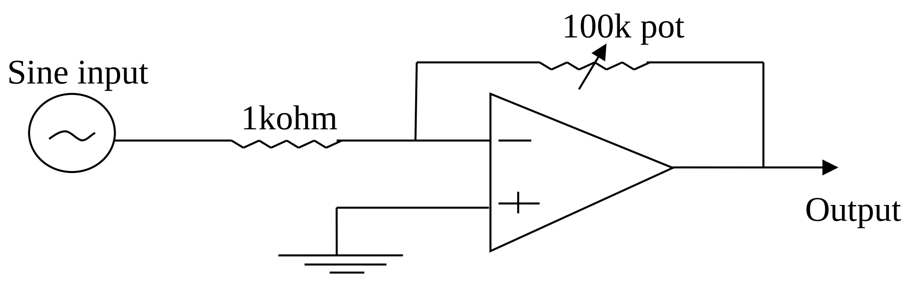

Fig 10- proportional controller

Then, we supplied a sinusoidal voltage wave from a function generator as input to the controller circuit. The input and output waveforms were viewed in a CRO. The results were noted and waveforms were traced in tracing paper. The experiment was repeated by varying the values of $k_p$using potentiometer. Results were viewed and traced.

Now, we needed to do the same test with the derivative controller. Here, we needed to supply a ramp input and check the output. Since, ramp signal cannot be generated due to saturation, so, we used a triangular wave input to the controller.

As we required 0<=k_d <=10, we use a 10 micro Farad capacitor, a 1K resistor and a 1M pot for the purpose, as shown in below circuit diagram. Waveforms were viewed in CRO and traced in tracing paper.

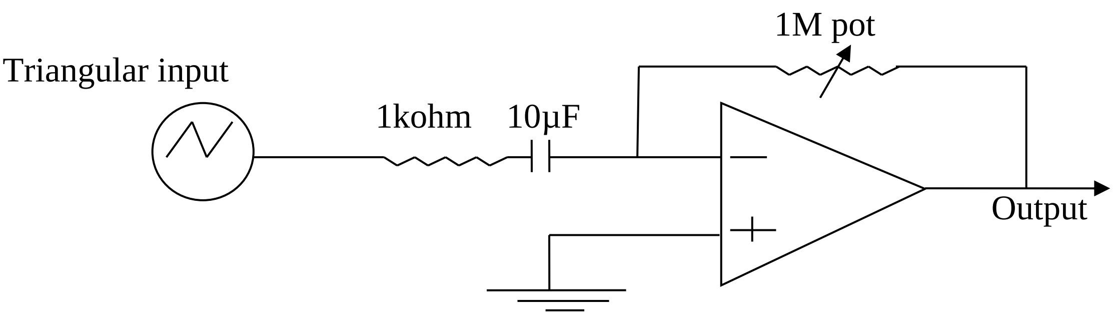

Fig 11- derivative controller

Next, we repeated the test for integral controller with circuit diagram as shown below. Components required were 1 micro Farad capacitor and 1M pot and a small, resistance say 1kohm was put in series with the capacitor as shown in the circuit diagram above.

Input given to the controller was a square wave. Output waveforms were viewed and traced in a tracing paper. Results were obtained for different values of $k_i$by varying the potentiometer. The same was repeated by replacing the 1 micro Farad capacitor with a 10 micro Farad capacitor.

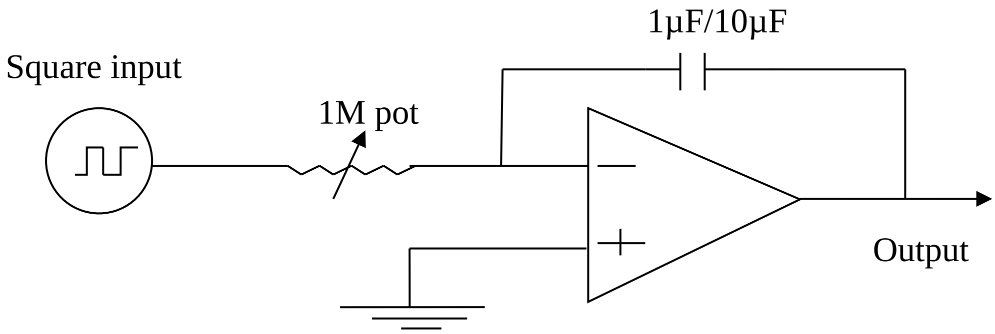

Fig 12- integral controller

Now, after performing these entire tests we move on to fabricate our PID controller .The circuit diagram for the design is shown below. The components used for whole process are shown in table below. The components are assembled together and the connections were made as per circuit diagram on the bread board. The supply voltages for the 741 opamps are not shown in the circuit diagram. Supply voltage of ±15V was given to the IC's. Then inputs were supplied using function generator and the required waveforms were traced on the tracing paper. Finally, after the testing the components were removed from the bread board and fabrication was started. Thus, fabrication of PID controller was completed.

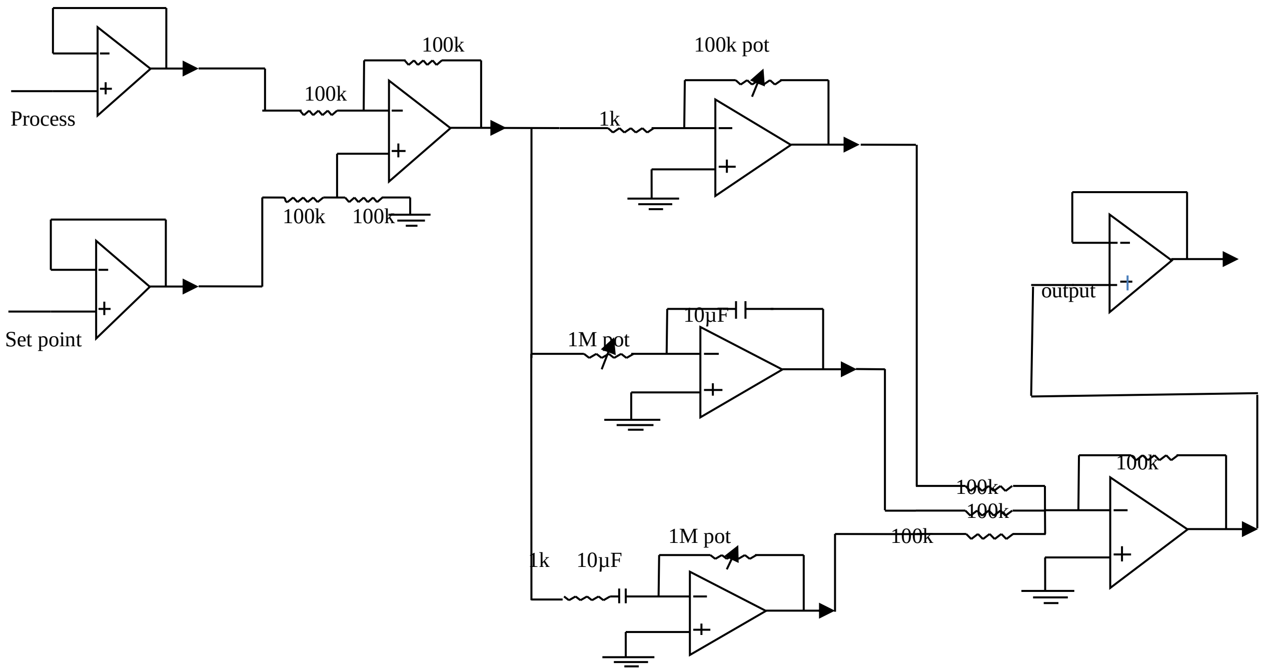

Fig 13- complete pid controller circuit

dedicated as input buffer, while one for output buffer. The process variable and set point variable are given at the input and we get the same values of input at the output terminals. Next, both the inputs are subtracted using another opamp IC which uses four equal resistors of 100k each. This generates an error signal at its output. The output of this is given to each of the individual controllers viz., proportional, integral and derivative. The controllers are nothing but three signal inverters with two resistors in proportional control and one capacitor and one resistor in both integral and derivative controls with their position exchanged in each. The output of the three controllers is summed up using a summer circuit and then passed through a buffer circuit. By using the buffer circuit, we are isolating the whole control circuit from outside loads. The controls of the variables are achieved using the three potentiometers as shown in figure. As we can see that proportional term contains a 100 pot, derivative and integral terms contain 100M pots, which is done in order to achieve required range of values of k_p, k_i and k_d.

In the derivative control, we find a small resistor of 1k. This is given in order to save the capacitor from short circuiting because we now that uncharged capacitor when connected to a voltage source acts like a short circuit initially. So, this resistor limits the short circuit current.

TABLE 4:-

Sl. No	**Components used**	**Quantity**
1	OpAmps (741)	8
2	100k pot	1
3	1M pot	2
4	100k resistors	8
5	1k resistor	2
6	1microFarad capacitor	1
7	10microFarad capacitor	2
8	Soldering kit	-
9	Multimeter	-
10	CRO	-
11	±18v power supply	-

12	Connecting wires	As required
13	Bread board/proto board	-
14	7815	2
15	Fan to fan connecter	As required
16	Berg strip	As required

Components used in fabricating PID controller

TEST RESULTS

The supply voltage given was ±18v through an adapter which was then converted to ±15V using 7815. Then required test was performed. After performing the test on proportional controller, it was found that the peak to peak value of sine waveform got reduced with increase in the value of k_p, and the waveform approached a steady dc value with almost no ripples.

The output of the derivative controller was a square wave corresponding to a triangular input as expected. The variation of k_d had practically no effect on the waveform except that there was a slight variation in duty cycle for variation of k_d from 0 to 10.

The output of integral controller showed both positive and negative peaks when a 1 micro Farad capacitor was used. When the capacitor was replaced by a 10 micro Farad capacitor the output waveform was similar to input wave with a large rise and decay time.

CONCLUSION

It was found that the proportional controller reduces the transients to an appreciable extent and thus, $k_p$should have high value. The derivative controller acts on the rate of change of input and thus converts the triangular wave to a square wave. It is very sensitive to changes or variations in the input.

As far as integral controller was concerned, it had a slow rise and decay time making system sluggish. The output waveforms were found almost as expected and thus, the analog pid controller was fabricated finally.

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