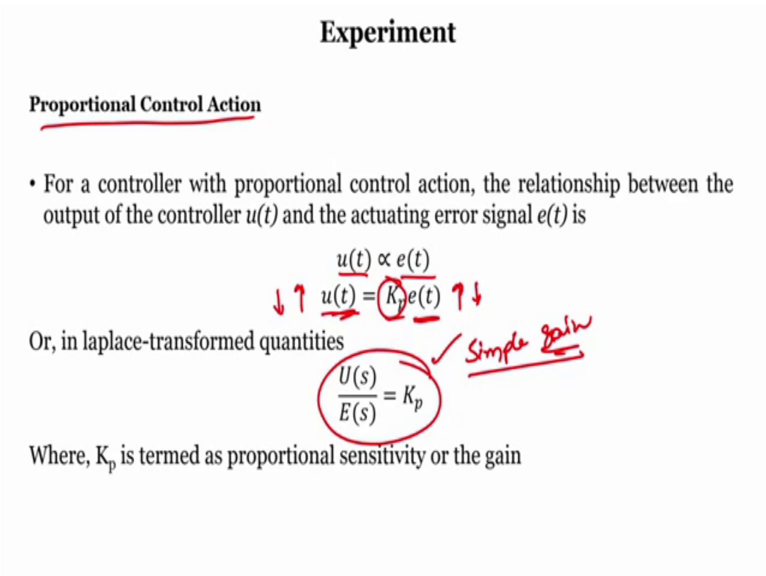
Op-Amp Practical Applications: Design, Simulation and Implementation
Prof. Hardik Jeetendra Pandya
Department of Electronic Systems Engineering
Indian Institute of Science, Bangalore

Lecture – 28
Experiment on Temeperature Controlled Circuit using Op-Amp as ON-OFF Controller and Proportional Controller

(Refer Slide Time: 00:21)



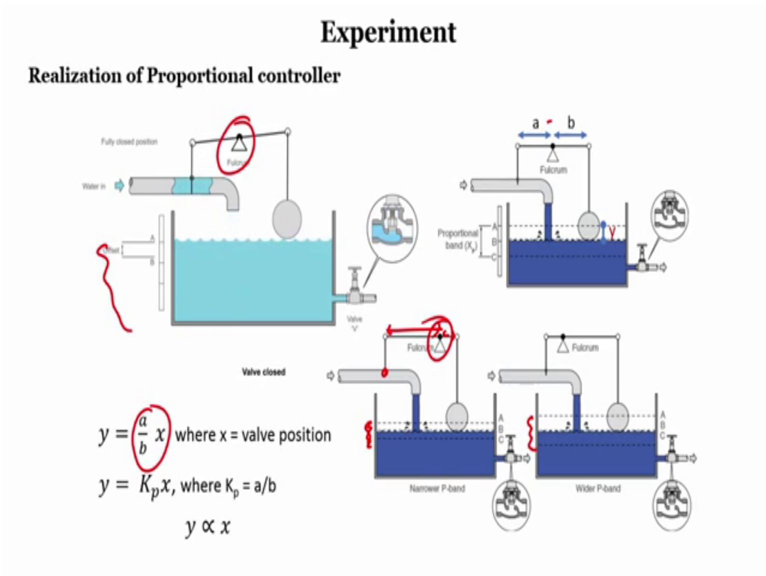
So now we will see how to proportional control action we will work, what is the difference between the previous control that what we have discussed was on off controller the relation at the difference between that on off control and the proportional controller. And, we will discuss and we will see how to implement the proportional controller using operational amplifier. So, in order to implement that; one thing, we have to understand how exactly the proportional controller works, what is the relation between your input and output. Once we know the relation between the input and output it is easy to develop are to design the circuit using on Op-Amp.

Now so, what is an proportional controller? So, the name itself says that, as we have also seen in the theory session, the proportional controller is nothing but the proportionate to that of here input. The input to the system is error and the output is always proportional to that of error. So, when we remove that proportional parameter. So, that means, the u of t is always equal to the proportionating factor K p right, which is also called proportional sensitivity are the gain of the system into error of t.

So, when we see when we convert into Laplace transform and if you observe it, it looks something like the gain of the system. So, a proportional controller is nothing but a simple gain so proportional. So that means, depends upon the error factor that will be always proportionally change. How much proportionally change? Or what is the scaling factor? Entirely depends upon the K p parameter, that is a tuning parameter in this case.

So, if your error is higher right the input voltage applied to the system to the plant will also be higher. If the input is the error is low, then the output of the proportional control system which is nothing but a input to the plant will always be low. So, that is entirely related to here error right. Error in this case input so that means how do we implement? So, when we recall we can either use an inverting, as well as a non inverting amplifier with proper gain. So, that gain we can said by using your feedback resistance. So, by using a part as a feedback resistor in inverting or non-inverting amplifier mode; so, this kind of a proportional action control action can be easily implemented using Op-Amp.

(Refer Slide Time: 02:44)



Now, when we see in order to now realize how exactly the proportional controller works, this is a simple example similar to the previous one. In a previous case we have seen that when the tank is almost at this position right, then it will switch on, switch off. If it is higher than this value it will switch off. And again if it is lower than this value then this will switch off. You have only option like either completely on or completely off. But in this case it is entirely depends upon the level of here tank.

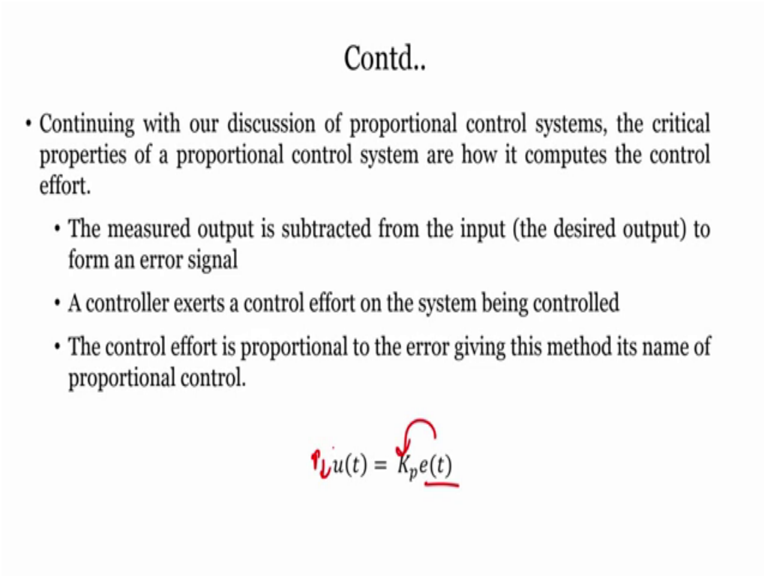
If you see the animation very closely so, this is where we have connected our bob, and this is where the valve right. When the level is lower, the there will be some flow of a water into the tank or some liquid into the tank, and the amount of liquid flowing entirely depends upon the position of the bob. If the position is at the higher position the output, the water in this case will be layerly smaller into the tank is smaller, right.

So, that entirely how much amount of water is being injected into the system entirely depends upon what is the level of your float. So, that means, if I want to change the you know the gain of the system in mechanical way. So, the position of this fulcrum decides right, decides the band of your system. So, for example, if A and B are equal right the output this offset it is nothing but a by b into x right. So, a by b is nothing but a gain.

Now, what if the fulcrum is in this position? So, if it is in this position the value of A is higher, and the value is B is lower as it is in the gain is higher right. So, that means, if you want to understand when the bob is at a low position more amount of input; that means, the valve will be completely at open completely open, right. So, more flow of water into the system right, the band if you see it will be completely narrow, when the flow is keep on increasing right, its it will suddenly there you can see a sudden close, sudden stop of your input right.

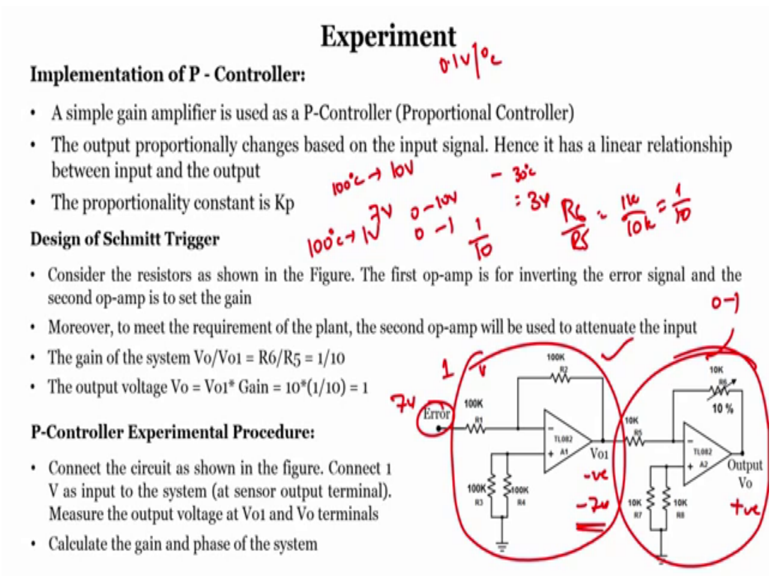
So, that means, this error band entirely depends upon what is a gain, what is a gain, what where exactly you are using the fulcrum whereas, if A is smaller and B is higher the result the gain is very smaller. It takes a longer duration which means that the band, the proportionality band will be even higher right. So, the proportionality band entirely depends upon what is a gain that you are using it. Or in order to understand what is the current the rate at which the current flow into our system depends upon the gain. Higher the gain, higher current initially and slowly decreases. Lower gain slowly it is right. This is the way to just to understand the mechanical; but since in our case we have to understand about the electrical way, right.

(Refer Slide Time: 05:52)



So, when we recall the input to the plant input to the system the controller system is nothing but error, right error signal which is the difference between here measured input and here desired output; say, point and the actual output. So, that difference input is connected to the K p, if the error is higher, higher input will be pump will be given as an input to the plant. If the error is smaller, smaller input voltage will be given as an input to the plant right.

(Refer Slide Time: 06:23)



So, that means, we require to use a simple gain amplifier, right. So, if you see this is a simple gain amplifier that we are using. Now excuse me, in this case the first Op-Amp A 1 if you see, the gain of the plant is 1, excuse me and whereas, the second Op-Amp if you see, right. So, the input to the first Op-Amp is error signal. So, the gain of the system is 1. So, because of that we will get a negative output voltage here, since we require the output to be in a positive condition we require to use another operational amplifier configuration; such that the output will be always in phase with your input signal 2.

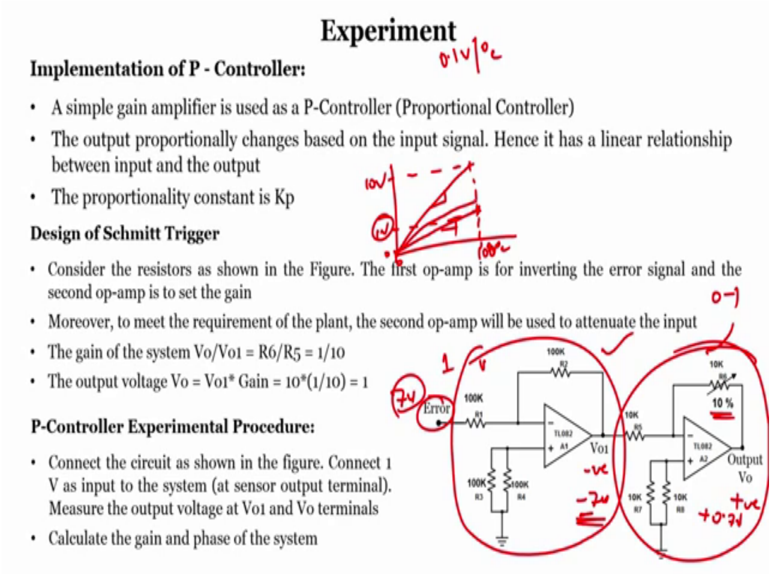
So, in order to do that, since we are using inverting operational amplifier we have to go with the 2 Op-Amps. Either gain can be set here at this point or even at this one thing. And another thing is that, when you observe the output should be always 0 to 1, right. Because the plant input range is only between 0 volts to 1 volt. So, in order to do that, we require to do some attenuation factor 2 right.

So, how do you understand this? The gain of the system entirely depends upon R 6 by R 5 in this case. Now we have taken 10 percent of 10 k which is nothing but 1k and R 5 in this case is 10 k. So, the gain is 1 by 10, right. Whereas, the gain of the first system if you see the system the gain is 1, right. Now, if you understand let us take the set point is somewhere around 100 degree; when we recall what is the proportionate output voltage. So, we remember 0.1 volt per degree centigrade is the sensitivity factor and 1 degree will be 0.1 volt.

So, since it is 100 degree it will be 10 volts. So, that means, when we are applying 10 volts is an input to the signal; meaning we are asking to maintain temperature to be 100 degree. Let us take 10 volt and the set point is somewhere around 30 degree; meaning, 0.3 volt, sorry 3 volt, 30 degree meaning 3 volt. Now, the difference is how much? The difference between 10 and 3 which is nothing but 7 volts is a error.

So, when apply 7 volts here, right the gain is 1. So, we will get an output as minus 7. Now, but minus 7 I cannot pump. I cannot give 7 volt as an input to the system, right. So, the complete range 0 to 10 volts, I have to convert it to 0 to 1 volt. So, in order to do that the gain of the system should be 1 by 10, that is the reason we are using another set of Op-Amp which is A 2 which has a gain of 1 by 10. So, that if it is if you are saying at 100 degree centigrade, right it will pump with maximum it will provide a maximum input voltage, that can be provided to the plant which is 1 volt to the plant. That is the output from the controller right. So, that means, what exactly we are doing? If I want to realize in terms of graphical way right.

(Refer Slide Time: 09:48)

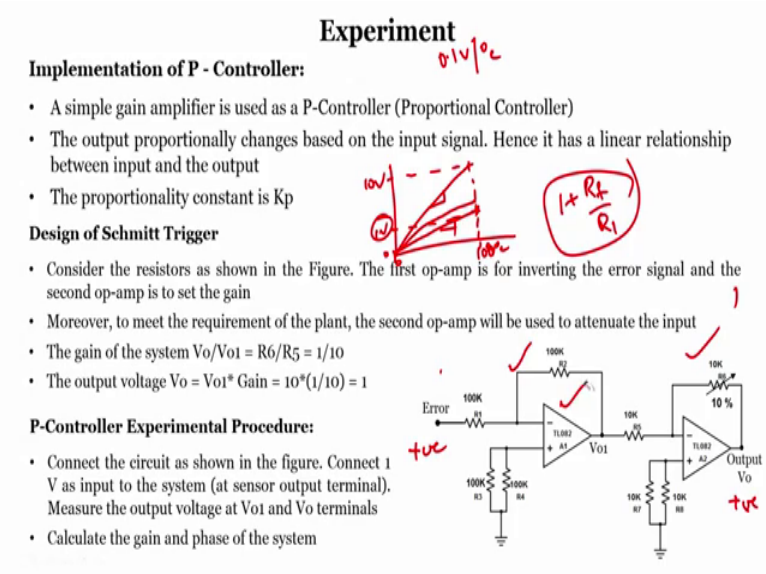


So now this is a graphical representation. So, for 0 it is at 0, right for 100 degree centigrade, 10 volt. Now we are I am changing a scale from 0 to 1 volt. Why? Because, 1 volt is enough is the maximum input voltage that we can apply to the plant. So, I just simply change this scaling factor by setting the gain here. So, the gain of the system is 1 by 10 right. So, if the input is 7 volt, error input is 7 volt so, the output will get is minus 7 so, this is minus 7. So, since the gain is 1 by 10, it will be plus point 7 volt, 70 percentage of full scale value.

So, even we can change the gain so, suppose if you need even. If it is 7 volts if you need higher value, we can change the gain by changing the R 6 resistance value, whether we need the same scale or different scale can be completely understood by using by changing the gain value, right. So, this is our signal conditioning circuit as well as well as implementation of AP controller using operational amplifier.

Now, why do we use this why do we require? This R 3 R 4 R 7 and R 8 resistance; as you have already discussed previously to compensate for bias currents Op-Amp bias currents. So, in order to compensate for that, we have to use we have to use the parallel combination of the feedback resistor and input resistances. That is a reason we are using same resistance (Refer Time: 11:38) understand the A 1 and A 2 the connections need not to be in the same fashion.

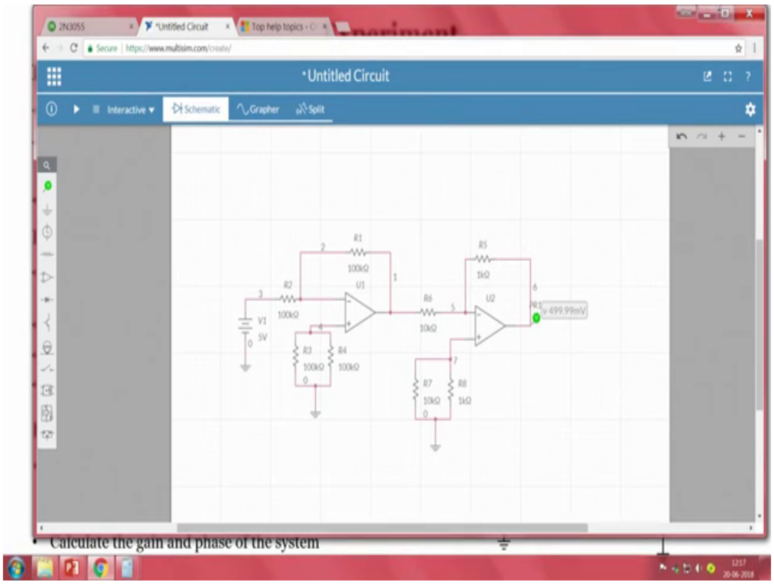
(Refer Slide Time: 11:45)



Our intention is when we are applying a positive, output should also be in the same phase. So, in order to do that since we are using an inverting kind of operational amplifier we are using 2 Op-Amps. The same thing can be realized using with the non inverting type of amplifier 2; where in such a cases you can simply go with simple one operational amplifier itself right.

But we have to closely select the resistance value, right. Because the gain of non-inverting amplifier is R 1 plus R F by R 1 so, that is the reason. So, here in this case, it is completely proportionate, we can easily understand, we can easily calculate, but if it is a non inverting it we have to put it on a calci or pen and paper. So, that is a reason we are simply using to make it little simpler, even though by using you know instead of using a single operational amplifier we using 2 Op-Amps. One is for changing of the phase, another one is for attenuating rate right. So, this is about P controller now so, in order to understand that, why do not we check in a simulation? So, this is I am going to create the same P controller.

(Refer Slide Time: 12:56)



So, when we see our circuit right. So, we are using the feedback resistor, which is of 100 kilo and one more 100 kilo resistor as input right. This is the error so, I am taking voltage source; which is nothing but my error right, this value will be ranging from 0 to 10 volts, right.

So, since the sensitivity of input, sensitive of factor of the input is 0.1 volt per degree centigrade, right for 100 degree it will be 10 volt. If it is 20 degree it will be 20 volt. But only thing is that your Op-Amp operating voltage should support that, right then right. So, we have to use combination of R F and R 1 resistors at the positive terminal; so that the effect due to by offset currents can be completely eliminated, sorry bias currents, right. I need one more which acts as an attenuation. So, what I will use it here? I will take so, in this case if you see the gain of the system is 1 by 10. So, that means, I am taking 1k 10.

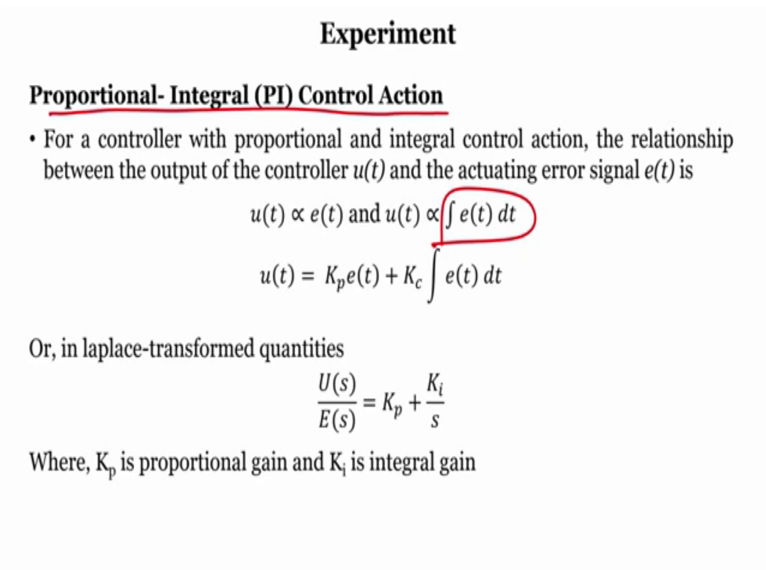
So, either we can go with an pot or we can use a simple 1k resistor 1k. And at this point it should be 10 k. So, the gain is 1 by 10, this is being applied as an input to this point. And this should be connected at this point, either the should be connected the negative. And we also require 2 more resistors so, what I will do is I will copy this. How do I copy? Pressure control select a whichever you want to copy and copy it here. If the resistance value should be different, one should be 10 k, other one should be 1k, right.

Now, let me connect output right. The gain is 10 so, since we have applied 1 by 10, since we have applied 10 we should get one not minus 1 that is it right. Now if I change it to 1 volt, it will be 0.1, 100 milli 0.1. If it is of 5 volts meaning 50 degree it should be 0.5, right half of here range. So, this is how here proportional controller. Now if I change the value, the gain value will not be in this 1 by 10 factor, it will be other factor right. How much what is the range with respect to the input? That we have to apply entirely decide by the gain of your system that gain can be completely set by using the feedback resistor, right.

So, please understand that the use of the signal conditioning circuit at this point this point is to attenuate, not only to provide the proper input signal to system it should also provide the same phase input signal to the system if you apply a negative of the same when it is of no use. So, that is a reason we are using 2 operational amplifiers to have the same phase and a feedback resistor with the lower resistance value compared to the R 5 resistor in this case. So, that the gain will be this will be then using at an amplifier we can use it as an attenuator. But the factor entirely depends upon what is a resistance value that here choosing in the in the feedback; which is nothing but R 6 right.

So, one thing is clear that the gain is 1 by 10 that we have already seen, and the phase of the system is same phase with respect to the input excuse me, ok. So, this is about the proportional.

(Refer Slide Time: 17:18)



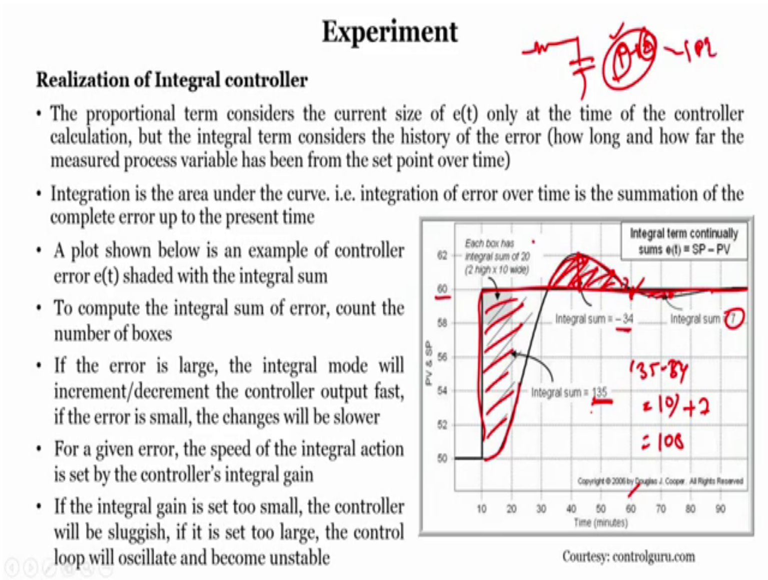
So now another kind of another way of implementing a system is by using proportional and integral. So, if you understand we are adding one more component into the system which is nothing but integration. So, what is an advantage of having an integration? We have seen that with respect to the proportional controller, the output will be proportionately changes based upon the error input. If the error is higher it will always higher. If the error is lower the output will also be lower. But if the error is constant, as long as error is constant, it will always maintain as the constant right.

But some cases we require some intelligence into the system meaning, even though if I am applying some input voltage, but the error the voltage the output temperature is always constant, right. So, such a cases, such a cases we require some intelligence saying that yes, since there is no response change in the output I have to add little higher value input voltage. So, such an intelligence humans will always have, but when it comes to a system how can you make that intelligence. So, that intelligence can be created by using an integration.

So, if you recall your mathematics what is an integration how does an integration does? So, integration is nothing but area under curve. So, in this case it not only depends upon what is a present error, it depends upon the summation of your previous error. The accumulation of a error, right that decides the that decides the manipulated variable in this case whereas, in case of a proportional controller you do not have such an intelligence. It completely proportionate, input changing, error value is changing, output I will change right. What factor it is changing? What is the gain that have said to the proportional control the same factor the output will change.

But if the if there is an error between input and output and if the error is always constant, it cannot either pump a higher value or lower value of the input voltage to the plant in order to reach to the required set point. So, because it does not have any intelligence; so, whereas, in this case it will always count, it will always add some if the error is constant the accumulation of error will be keep on increasing as a result it changes here output voltage.

(Refer Slide Time: 19:42)



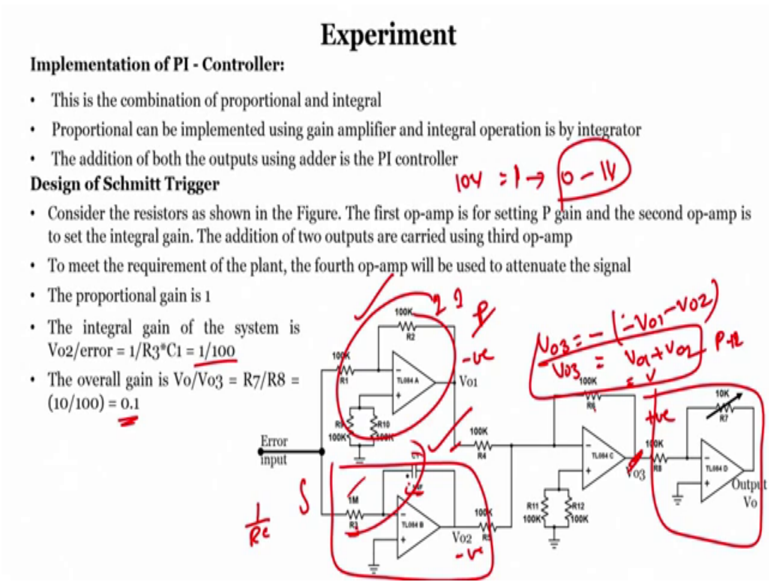
So, as we have already seen in the theoretical explanation by professor; so, just recall so, if I say this is my threshold, sorry this is my set point. And this is how the output is keep on changing right, keep on changing when you do an integration what it does is that, it will add sub the error factor. So, this is the dashed lines is nothing but the error output right. So, it adds up at this particular point what is an error that I have so, that sum is 135.

Now, if it is keep on continuing right. So, the error will be keep on accumulating as a result output will change. Suppose, if it is at 60 so, the integration sum will be minus 34 here and this is 135. So, the error is so, because in this case it is little higher compared to the set point, right. So, with 135 value the quantity of 135. So, it is going to you know more than the required set point; that means, 135 is not a actual value. So, I have to decrease it, how much amount it is to be decrease, entirely depends upon how much variation that we can observe here.

So, as a result the value that will be applied is 135 minus 134, sorry, 34 which is somewhere around 101. But if I apply this 101, again there will be some understood, there is some overstood here, there is an understood. And if you calculate the error is 7 so, 101 plus 7. So, application of one naught 8 quantity it will maintain constant, right. In case of a proportional if you realize, if the error is higher the output will also higher right; that means, if I say the error is this output also this, error is smaller output is smaller. It does not depends upon the accumulation of errors in case of our integration, right.

So, that is that is the intelligence that we are creating. So, since we are using integrated in the system, the complexity of the system is also increasing. But how do we design? How do we design using an Op-Amp? So, one thing we have to understand, using an Op-Amps any kind of operations that we can do. So, integration we can do differentiation we can do, if you recall the way of doing integration by simply using of your resistor and a capacitor it does an integration operation. And it is a combination of integration as well as proportional we have to take an adder which adds with the proportional controller, and which adds with the integral controller. The addition of these 2 is nothing but my pi controller.

(Refer Slide Time: 22:31)



If I see the complete system, if you observe that the A portion of TL 084; so, TL 084 is a quad Op-Amp. So, it has a 4 Op-Amps inside the A portion of TL 084 first Op-Amp has a gain of 1. So, which is acting as a p, and if you see this B portion of TL 084, a resistor and a capacitor, it acts as an integrator, right. I got p with a gain of 1 and I got integrator and the factor that the time factor entirely depends upon what is a resistor that we have chosen, right. Which is nothing but 1 by RC, right. So, 1 by 1 by RC is the kg, which is nothing but the k i propose integration gain, right.

So, I have implemented using the operational amplifier the proportional controller, implementation of integrator using operational amplifier is an, but proportional controller is addition of p and i. So, we need to have an adder. So, this will have a negative phase shift, this will also have a negative phase shift so, no problem. So, I am taking a negative adder right, I am taking a negative adder. So, the output will be positive right.

So, what it does? If I say this is V 1, V o 2, V o 3, will be minus off R 6 by R 4 since both are same resistance value it will be the gain is 1, minus of minus V o 1 minus V o 2; so, which is nothing but V o 1 plus V o 2. So, we are getting a gain, we are getting V o 3 as the required pa controller output. But what is the value it will be? The value will be entirely depends upon what is the gain that we have setting here, what is the value of this right?

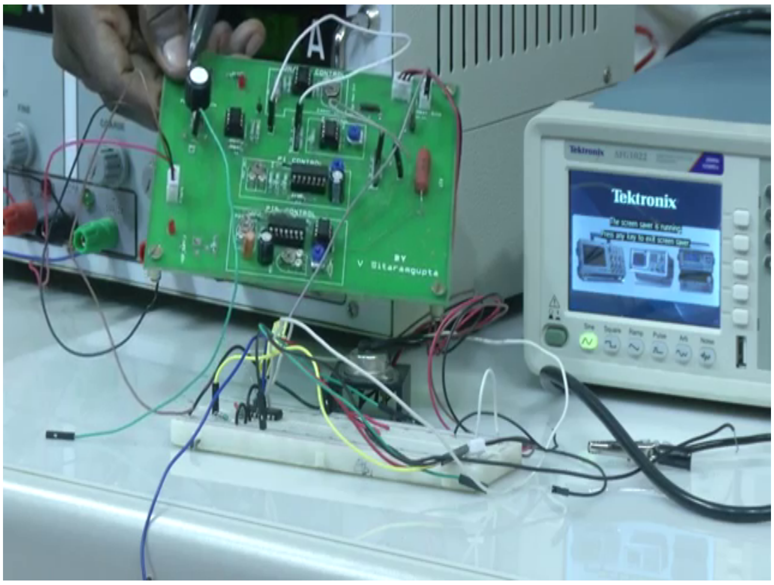
So, the addition of these 2 will be some other value. But, is this voltage is good enough to pump my give as an input to the plant may not be. Sometimes the output will be even at more than 10 volts, but I require the voltage the range of the input voltage to be given as to be of 0 to 1 volt for the plant. So, in order to maintain that range, we are using one more operational amplifier one more operational amplifier right which attenuates, when you see the gain of the system is 1 by 100 in this case ok; so, which will attenuate that right.

So, the proportional gain is 1, the integral gain is 1 by 100, right. So, the overall gain of the system is 10 by 100 which is 0.1, because some overall gain if I want to calculate V naught by V o 3 right so, this gain is 0.1. So, compared to the voltage whatever we get, it will always multiply with a factor of 0.1. So, that even if the input voltage somewhere 10 volts it will be at 1 volt; so, which will match to the plant requirement. What about the phase? If you see when you observe the error right, error, error will be always.

So, let us take this is the input, this is set point 60, 60 minus 50, 10 right. When the input is 10, this will give minus, these give minus. This will give positive, but the again is gives negative. But we require a positive; that means, we have to use one more operational amplifier which converts which will always maintain the same phase. Or rather than using a simple inverting configuration we have to go with non inverting configuration with the same R 7 as a part. So, that the required gain can be set by using R 7 resistant right; so, the phase should be very much important, ok.

Now, right so since we have already seen integrated in the previous lectures, when we are discussing it with the filter, I am no I am not going to show anything about the filter anything about this, but just understand I understand the complete working of this.

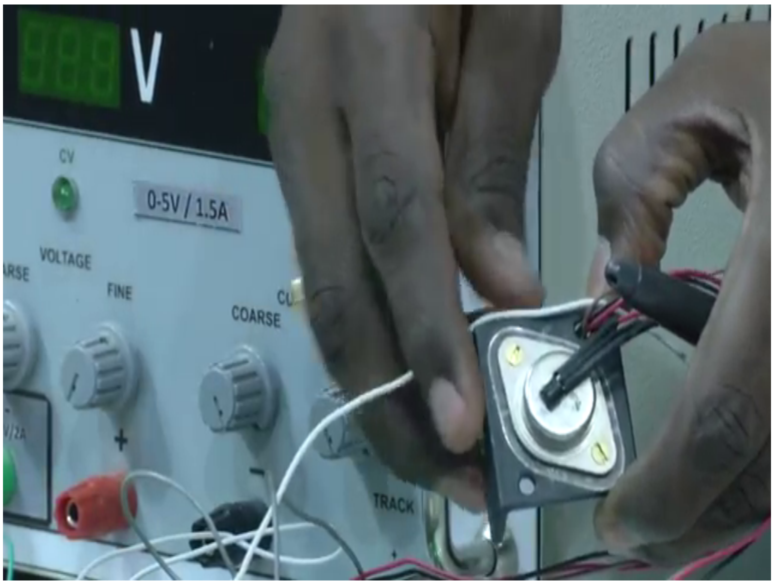
(Refer Slide Time: 27:26)



So, now where we look into the board the complete the blocks that we have discussed till now is implemented using this particular board. If you see this is the input voltage this is a part, this is a part, this is the input voltage which we are setting by using a part. So, whatever the input voltage? Like say 1 volt, which is nothing but 10 degree, 2 volt which is nothing but 20 degree right; that voltage we can set by using this particular knob. If I keep on changing it that is a point parameter will always change.

Since the sensitivity factor is 0.1 volt per degree centigrade. So, depends upon what voltage we are applying right will decide. Now this is our error amplifier right, error detector. So, error detector is a simple differential amplifier. So, what we have used is so, this is TL 0 A 2. So, TL 0 A 2 it has 2 Op-Amps, 1 Op-Amp is simple voltage follower in order to not to have impedance mismatch between the output of the part to the differential amplifier. The output of the part is connected to the voltage follower, and the output of the voltage follower is connected to the differential amplifier. Whereas, other input other input to the error detector is from the sensor.

(Refer Slide Time: 28:51)



So, what we are doing is so, this is our sensor. This is the black color one, the black color one is connected to the signal conditioning unit in the breadboard. So, if you see these are breadboard. So, by using another operational amplifier, we are using we are designed a signal conditioning circuit what we have discussed in the in our experimental. So, the same gain everything is set the same resistor whatever we choose, the same resistors even being used in this case and a signal conditioning is set.

So, as a result, the sensitivity factor of the input as well as the sensitive factor of the sensor output will be always at the same point. So, it is easy when we do a different when we do subtraction. So, that is the reason the output from the breadboard is connected to the input of the system. This input is connected to another terminal of air Op-Amp of the differential amplifier. So, as a result it gives an error output. That error output we can tap using this right. This is small kind of marks. So, we have different types of controllers here. So, we can see, the first controller is on off controller. So, this is 180-ohm resistor that we have chosen. So, if you recall we have use 3 resistors R 1, R 2, R 3 right, all 3 resistors we can see.

And, we have use on off controller with signal conditioning circuit right. So, since this is TL 0 A 2 with a single Op-Amp we can design Schmitt trigger plus signal conditioning circuit. The attenuation is completely done by using this Op-Amp, sorry, this resistor pot, right. Below this we have a P controller. So, we do have a P controller so, P controller this is TL 0 A 2 so, it has both Op-Amps. So, the signal conditioning and P controller what we have seen is completely implemented using this. Other one is TL 0 8 4, it has 4 Op-Amp; so, we are using only 3 Op-Amps right. The gain is completely set by using because the feedback resistor or we can go with the initial P gain.

So, we can see capacitor and one resistor, which is acting as integration right. Another part if you see this is another part; which is useful for the overall gain of the system right; the completely similar to our previous one of the circuit that we have seen. So, it this board also has another portion called PID controller portion here, right. So, it does both proportional summation of proportional output, integration output and differentiation output, right.

So, since this is not part of our course, we have not discussing about the PID controller, right. Also we have another Op-Amp here. So, this Op-Amp is a signal conditioning unit or the plant part of a plant. If you recall, if you realize what we have discussed in the plant circuit, we have use in a, we have used a transistor as well as an Op-Amp. So, that Op-Amp is taken from this, and this is a 5 watt 0.1-ohm resistor, right. So, since I am going with the minimum current of a 3 volts 3 amps, I am not going with the 5-watt resistor, sorry, 10-watt resistor, I am going with 5-watt resistor.

So, depends upon your requirement depends upon the source requirement, we can even change the resistance value. So, what changes is the respond sent, how fast it is heating, entirely depends upon what is the resistor that you have chosen right. And that is being connected to your transistor right, the same way right. Now, if you see the board closely to which controller that we want to connect right. By using this burr connector by using these jumpers we can decide. So, this is an error output, suppose if I want to use on off controller, I can connect the output of this 2 on off controller, right.

So, that this particular portion is connected to the on off controller input to this, then it gives an output here right. Since, if you connect to on off controller, the output should be connected to the on off controller; like a like a mux and de mux. If I want to use P controller, we have to connect the jumper wire between the error output to P controller. So, that this particular block will be using it, right. So, to PI if I want to use this portion, the jumper has to be connector from here to this point. Similarly, even at the output side to from the PI 2 output we have to connect it, right.

So, I hope it is clear the working of you know the placement of different components in a board. So, since we are using different operational amplifiers and the operating volt is plus or minus 15, that completely set by using this particular RMC connector, right. So, one is plus 15, the other end is minus 15, the middle part is our ground, right. So, 3 can be connected here so, that once we connect the power supply to this, we can see turning off the LEDs. So, this LED will turn on only if you have a minus 15 connector, more than minus 10 volts. This will be switched on only if sorry, this is for positive and this is for the negative supply, right.

So, we will see the theoretically whatever we have seen as well as whatever we have explained we have seen in the simulation, the same thing we will see even in our experimental tool. So, rather than like I may not be completely showing you the complete block by block, but by connecting it, by changing the gain the complete operation of a controller as well as this the controlling, how exactly the output of the output of the controller as well as the desired output is matching with your set point; that we can see right.

So, that we will see in the next class.