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

Lecture – 26
Experiment on Temeperature Controlled Circuit using Op-Amp as ON-OFF Controller and Proportional Controller

Welcome, to the module. In this module, we will see the other application of our operational amplifiers as a controlling. So, as we have already seen in the theory session so, we are going to look into we are going to design and implement an closed loop control system in this particular experiment.

(Refer Slide Time: 00:50)

Experiment: To Design and Build a Temperature Controlled Circuit using op-amp as ON-OFF Controller and Proportional Controller

Introduction

Temperature control is a process of maintaining or controlling the temperature of the system to a specified value by continuously assessing the current temperature of the system and adjusting the system parameters in order to meet the user requirements.

Temperature monitoring is very important in industries as well as in the research. Especially, in food and pharmaceutical industry temperature control is vital.

One way to control the system is by using a simple closed loop system. But it is important to understand the effect and requirements of a system before implementing it. A simple and low cost controller used is of ON-OFF Controller which merely switches the heater either ON or OFF when the temperature rises or falls below the threshold as per the design. This makes the system to continually switches OFF or ON as per the input received from the controller and all systems cannot be accepted. The actual temperature is the calculated as the average of overshoot and undershoot of the temperature. A much more expensive method is by changing the input based on the error by calculating the difference between the required temperature and the actual temperature. This minimizes over/undershoot depends on how complex the controllers we use

So, the whole idea of this experiment is to design and build a temperature controlled circuit using op-amp as an ON-OFF controller and the proportional controller. So, when we recall our theory session we have seen the importance and we have also seen in the applications of a temperature control in an industry as well as even in our research fields too. Now, based upon the criticality how good that we control the temperature the cost also matters.

So, in this experiment what we do is that we will see how can we generate a temperature on a system. So, that system is nothing but a plant. So, what is the logic behind that, what is a design parameters and what is a logic behind that, how it is heating the plant and we will take some temperature sensor on top of the plant because we require to measure the temperature, what is the temperature that is there on top of the plant. So, for that case since the temperature is one physical phenomenon and since we are implementing a controller to control the temperature on the plant by using some analogue circuitry so, we require to have an electronic input. So, electronic input is nothing, but either voltage or current.

So, we have to take a transducer or a sensor which converts a temperature changed to an electronic output voltage. So, far that case we will take a temperature sensor which is of LM 35. Now, we will see how an LM 35 will work and what signal conditioning circuitry we require, why do we require the signal conditioning circuitry for the sensor before connecting it to the controller. Now, as we have also seen the importance and what different types of controllers that can be used and the how complex the controllers are. In the theory sessions we will see how can we implement the controllers that we have discussed that that professor has discussed in the class using our operational amplifiers their working, their designs and their practical you know the practical the results with respect to our experimental results, I mean simulation results with respect to the experimental results. We will try to compare and we will also try to compare with our theoretical results too.

(Refer Slide Time: 03:05)

Experiment: To Design and Build a Temperature Controlled Circuit using op-amp as ON-OFF Controller and Proportional Controller

Aim:

- The major task is to control and maintain the temperature on the plant as per the user requirement. This requires a plant which generates heat. One way is designing a plant as a heating source using transistor which produces a heat because of high power
- The control action needed to bring the temperature to the desired set point were obtained by designing a basic controllers with an objective of minimizing error for settling

Objectives:

This project consists of two objectives as listed below:

i. To implement a circuit for heating the transistor
ii. To implement a controller to maintain the temperature of the transistor to the required set point

Now, when we recall when we look back into our complete aim and objectives of this. So, first part is that, the main objective of the system the main aim of the system is to bring the temperature to desired set point, right. So, when I say 50 degrees the plant has to always maintain a temperature of 50 degree, when I say 100 degrees the plant has to be operate at 100 degrees. So, operate in the sense it should always maintained it should always control at temperature of 100 degree centigrade or at 50 degree centigrade

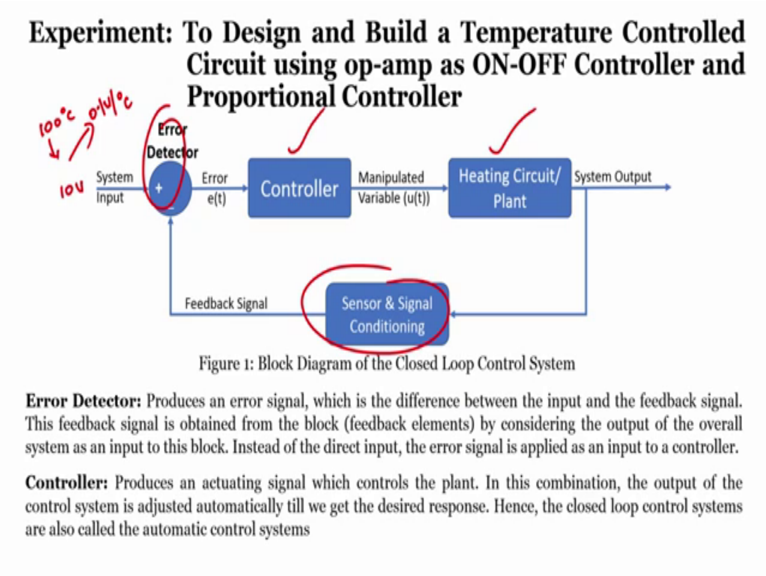
Now, so, in order to control it we should know what is so, we should know what is our you know the specifications of our plant, how the plant will work like, right. We should also understand how we designed our plant, right, what input that a plant is required in order to heat the system, whether it is a current or whether it is a you know voltage and how much input voltage that we have to give it; meaning power how much input current or input voltage we require to heat the system and what is the maximum current or what is the maximum voltage or what is the maximum power that the system can withstand without damaging it.

So, once we know all these parameters, we can design our controller or feedback controller or controller for maintaining the controller for maintaining or controlling the temperature on a plant. So, the objectives in this case is that to implement a circuit for heating the transistor that is the main major thing. So, we have to see we have to implement a circuit for heating a transistor we will see and we will also have to see how do we implement a controller to maintain the temperature of the transistor to a required set point, you got the point?

But, when I say required set point so, when we see when I say required set point which is nothing, but we will always think about 50 degree that is my set point I always have to maintain the temperature of the plant to be 50 degree or 100 degree. But, how an electronic hint will understand 100 degree when I say, 50 degree when I say? So, it cannot understand. So, in order to make the electronic system to understand our intention the human intention we require to do some mapping. We require to do some mapping, so, or some scaling factor which converts our input temperature to input voltage some kind of a sensitivity or some kind of a scaling factor has to be decided.

So, now, we will see one by one. So, we will take this particular object to the last and we will see how can we use how can we implement this particular part. So, by using an operational amplifiers such that the major thing is that we need to bring the temperature to the desired set point by designing a basic controllers with an object of minimizing errors for settling, that is a whole idea.

(Refer Slide Time: 06:07)



So, when we look into our basic so, in order to implement the system one thing is we should understand how a closed loop control system looks like. So, if we recall our theoretical session what professor as discussed, this is the basic simple feedback system. So, in case what we are going to do is that we will see how can we so, when we write in terms of block wise it is easy to see it easy to write a block. But, when it comes to implementation that to when we are putting on a hardware or when you are doing on a breadboard we should understand the working and based upon that we have design the system you should understand the working of each and every block and we have to put it.

So, before putting it we should understand what is the importance of this tool, right? So, when we recall what is the importance of the error detector the purpose of an error detector is to compare the signal output with the system output system input with the system output. So, what you mean by system output? System output is nothing, but what is the current temperature that is there on the plant at what temperature the plant is operating at system input is what user wants to maintain or what user wants to keep the plant at a point.

So, like say when I say the system input is of somewhere around 100 degree centigrade or 50 degree centigrade. So, in order to understand in order to understand so, in order to understand that so, considering so, like say the user wants to maintain the input as 100 degree centigrade. But so, but initially when we see the heating circuit or the heating circuit will be at room temperature; room temperature meaning somewhere around 25 to 30 in between it depends upon where we are at. Now, now the temperature of the plant is 25, but the required temperature is 100 degree centigrade. So, which are not matching and moreover, when we see the term 100 degree; 100 degree is our understandable temperature units, but electronic system does not understand 100 degree. So, we have to provide the input in terms of voltages in terms of voltages.

In order to in order to and in order to put one particular factor scaling factor what I consider is, I will consider 1 volt per degree centigrade, meaning when I say sorry 1 volt per 10 degree centigrade or 0.1 volt per degree centigrade is the scaling factor or sensitivity factor. Meaning, when we give the input as 1 volt; that means, I am telling my system to maintain at 10 degree centigrade when I give the input as 5 volts I am saying the set point of the system is somewhere around 50 degree when I give input as 10 volt; that means, the system set point is 100 degree, right. So, since electronic unit is only the understandable input to the system the complete system we have to convert the degrees in terms of voltages. So, this is what the factor that I am choosing it, right. So, this is clear. So, this is clear for us.

So, what I will do is that so, rather than saying 100 degree. So, I will say 100 degree if I do it the input that I have to provide is 10 volt. The reason is that the factor is of the factor what I am considering is one point 0.1 volt per degree centigrade, right 0.1 volt per degree centigrade. So, since it is 100 degree so, it is nothing, but 0.1 by you know 1 degree is corresponds to 0.1 volt. So, if it is 100 degrees it will be 0.1 into 100 which is around 10 volts. So, if I apply input as 10 volts; that means, I am I am saying the plant to be this particular plant to be should be at 100 degree.

Now, it will always start at 25 degree because since it is a heating plant, right. So, if we see that it will always be in degree centigrade, right. But, how a system will understand how this particular system will understand at what temperature if it is at degree centigrade, right. Physical parameter when you see the temperature is heat it is not an electronic unit. So, we require some system some transduction or some kind of electronic unit which converts the heat input into this electrical output. So, that is nothing, but a sensor.

So, if we recall the difference between the sensor and transducer, a transducer which converts one form of energy into any other form of energy. Any form of any form of energy to any other form is called transducer, but whereas, the sensor is nothing, but any physical input any form of input will be converted into electrical output change electrical output change; it can be resistance change, it can be current change, it can be voltage change, impedance change anything. So, that the system which can which does this particular functionality is nothing, but a sensor.

So, even in this case temperature is heat where by touching only we will understand that. So, in order to give it as an input to the system, this particular system we require to convert this particular system to electrical output by using a sensor. So, for that we are using LM 35. So, we will stick LM 35 on top of our temperature sensor or on temperature plant, right. Now, now why do we require the signal conditioning at this point? Of course, LM 35 will also give an electrical output voltage, but it is not guaranteed that the output voltage that we get from the sensor is equivalent to the factor that we have decided here, right. It may or may not equal to. So, in order to understand how exactly this system works. We should look into the datasheet of LM 35.

So, when we look into the datasheet of LM 35 one particular factor that we can see is sensitivity. So, the sensitivity of LM 35 is 10 milli volt per degree centigrade. So, when we look into the datasheet the sensitivity of LM 35 is 10 milli volt per degree meaning ` degree gives me 10 milli volt, right. So, since it is a 25 degree centigrade when I see 25 degree I will get 250 milli volt, right. 250 milli volt meaning 0.25 volts I will rewrite which is nothing, but 0.25 volt.

Now, if the sensor gives me 0.25 volt since I am passing the input to this point, right so, this is 10 volt, this is 0.25 volt. So, when it comes to realistic way from the sensing point of view 0.25 it is easy to understand it is 25, but when it when it comes to with respect to the input, where the sensitive factor is 0.1 volts per degree centigrade. So, since it is 0.25 volt it is nothing, but it is a 2.5 degree centigrade, right. So, which means that both the factors the input factor the both the factors which are nothing, but the input factor as well as the output factor both are not matching, that is because of the sensitivity. This particular factor change, this is 0.1 volt per degree centigrade this is 10 milli volt.

Of course, we can also consider we can also consider 10 milli volts per degree centigrade, but it is very hard to provide accurately such a small input voltages to the system, right. So, because of signal to noise ratio because of you know the electronics section so, but if you see the very it is easy to provide 1 volt, 2 volt with almost negligible change in the output. So, that is the reason rather than changing this particular factor to 10 milli volt per degree centigrade we will convert this factor to this particular value. Say if I multiply the factor of 10 so, 100 milli. So, to this 10, if I multiply so, what will be if I multiply with that 10 into 10? 100 milli volt per degree centigrade. So, which is 0.1 volt per degree centigrade. So, which is matching with this particular value.

So, in order to provide this particular factor of 10, we require to use a signal conditioning circuit. So, in this module we will see how to implement the signal conditioning circuit for LM 35 to the design parameters, why we are using it, everything. Once we get a signal out of it that has to be that is the output is nothing, but the feedback signal from the sensor will be compared with the input signal with the input signal. Now, since it is multiplied with the factor of 10 you will get an output as 2.5. Now, what is the difference? If I want to see the error when you recall what an error detector does? It does the difference between input and the feedback signal.

So, when we do that 10 minus 2.5 which is nothing, but 7.5. So, the error signal is nothing, but 7.5. So, how it is doing? We have to subtract, one the system input with the feedback signal, right. So, in order to implement that particular logic using operational amplifier one way is either we have to go with a instrumentational amplifier or with a difference amplifier. So, either we can go with a difference amplifier or instrumentational amplifier. It depends upon which one you are going with, but if you go with an instrumentational amplifier it may be little higher cost higher cost, but the input impedance on the CMRR will be really good.

But, if you go with a difference amplifier even then that is more than enough for us in this application since the signal the signals whatever we are getting is not almost the common signal. So, it is more than enough for us to go with a simple differential amplifier rather than you know 3 op-amp based instrumentational amplifier or any kind of instrumentational amplifier at this application. So, to implement this error detector one thing is we should understand how to implement difference amplifier, right. So, now, after implementing difference amplifier it gives me 7.5 volts, right.

Now, now we should understand how does a controller works, what different types of controllers that we are looking for, what are the functionalities of the controller, what is the logic behind the controller. So, we will go with ON-OFF controller we will see how does an ON-OFF controller works in this case, what does the ON-OFF controller do and how proportional controller does. Since we have already discussed in the theoretical session as professor discussed in the theoretical station about proportional ON-OFF controller, we will see how do we implement the strategy of on and ON-OFF logic of ON-OFF and proportional controller using this particular op-amp and we will try to implement here.

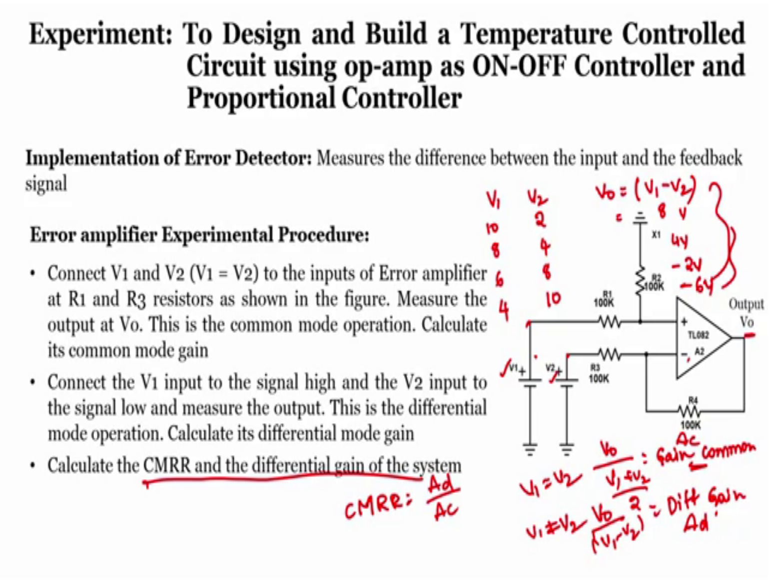
So, once the error signal pass the controller, controller will take an action how much amount of input voltage or input signal which is nothing, but manipulated variable to be provided to the heating circuit, so that the system can quickly heat to the required system input. So, system output will be always match with the system output will be always match with the system input. So, that call will be taken by controller, but that requires some kind of an user input. It depends upon what controller that you are using that user input are nothing, but our the tuning parameters. So, how fast to reach, how much time are required to settle down, right what is a over should that we are getting whether such high amount of current is to pass through the system in order to have a quick response quick you know ramp to the to the desired set input, is it to the plant or not, everything will be decided by the tuning parameters of the controller, right.

So, we will see how can we implement those controllers using operational amplifiers, we will design it then the controller will give one particular output which is in terms of a voltages we have to understand whether the heating circuit can take input as voltages or not. So, in order to understand we also have to understand of the heating circuit. So, if I can implement one by one using operational amplifier, right using operational amplifier it is easy for us to understand the complete circuit. As well as, in case if you are getting a problem at this point we can rectify the problem and I can indicate with complete system and we can see the complete operation and controlling of the system.

So, what we do is that, we will build, we will build each and every subsystem, we will convert this complete experiment to different subsystems. We will take one particular subsystem, we will build it. So, similarly all other subsystems we will verify the functionality with a theoretical, practical and experimental if both three are matching it then we will integrate everything together and we will see how the responsible will be off, right. So, that is a complete plan of our this experiment.

Now, so, one thing we should be keep in our mind what is the input sensitivity or input scaling factor that we are using for the system, right. So, which is nothing, but 0.1 volt per degree centigrade, that should be always we should keep in our mind because since it is an electronic system we should always have to give in terms of voltages only,.

(Refer Slide Time: 21:18)



Now, so, we will start with simple error detector. We will start with a simple error detector which is nothing, but a differential amplifier when we see, right. So, this is a differential amplifier circuit, right. One input will be connected to the R 1, R 2 pair resistor pair other input is connected to the negative terminal which input of R 3. So, the output will be so, if you recall the working of differential amplifier, the output is nothing, but V 1 minus V 2 into R f by R 1, R f by R 1. This is a case when if R 1 is equal to R 3 and R 4 is equal to R 2. Since in this case both R 1 equal to R 3 R 1 equal to R 2 equal to R 3 is equal to R 4 so, R f and R 1 values are same. so, the gain of the system is 1.

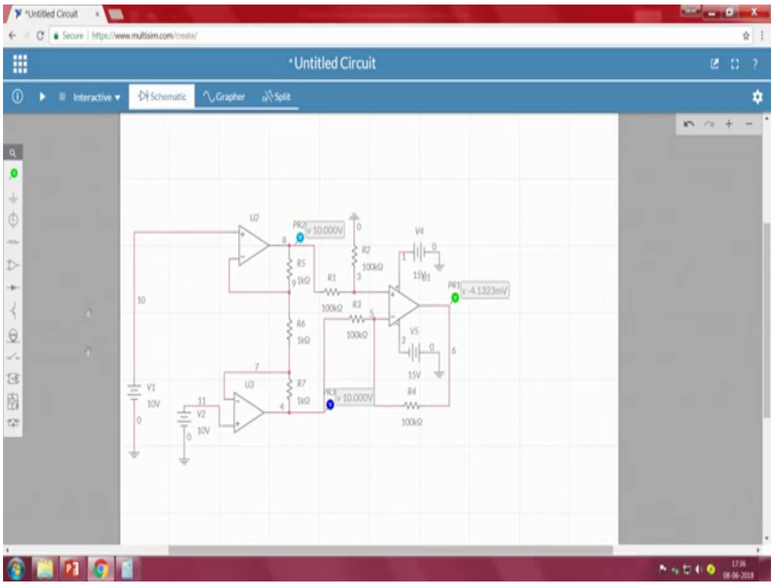
So, the V naught is V 1 minus V 2, that is what even we required, right. When we recall our system we do not have to apply any gain, what are the input I have it has to be subtracted with the feedback signal and I have to get an output that output we call it as an error, right. So, in order to give that I do not need any gain. So, since I do not need any gain I am using all the resistance of same value. So, that is may be the problem with instrumentational amplifier. So, few instrumentational amplifiers will have a gain starts from 5, the commercially available monolithic instrumentational amplifier IC the minimum the gain that will have is 5. So, since it is not possible in this case what we have to do is either we have to go with a high input impedance differential amplifier, right. So, I understood how exact. So, we already know how does it works.

So, let me quickly look into the simulation. So, so in order to understand about the simulation whether it is working fine or not what we will take is we will take different points. So, let us say I will take V 1 and V 2 and I will calculate V naught. So, V naught when you recall it is nothing, but V 1 minus V 2, the input that I am applying at this point and this point, right. So, let me take one input as 10 V 1 and another input as 2. So, that means, 100 degree and 20 degree. So, what will be the V out? V out will be 10 minus 2, 8 volt I should get an output as 8 volt, right. So, this I am taking 8, this is 4. So, V out will be 8 minus 4, 4 volt, 6, 6. So, I will go with 8 in this case I should get minus 2 volt, right and 4 and 10, I should get minus 6 volt. Let me see whether I am getting these values if I design in a practical system.

Now, in order to understand about the gain what we do is that we will we will in order to you know practical as well as theoretically to calculate the gain as well as the CMRR value of the system what we can do is that we can apply same signals at V 1 and V 2 and we will see what is an output voltage we are getting. So, we know that V out by the input voltage that we do with we connect is nothing, but a gain of your system, right. When we connect the same signals V 1 plus V 2 by 2 will be the common mode gain because at this point we are taking V 1 is equal V 2, we will get common mode gain.

Now, we will take different values of V 1 and V 2 and we will calculate what is an output and divided by V 1 minus V 2 this is nothing, but our differential gain now if I want to calculate my CMRR. So, CMRR is nothing, but differential gain by common mode gain. So, what are the gain that I am getting this is Ac and this is Ad, this divided by this if I do I will get the CMRR of the circuit. We will see theoretically now and then we will compare with practical too, excuse me. So, to understand that what I will do is that I will open a multisim, so, let me create a circuit. So, so we are using multisim from. So, many experiments I do not have to explain about how exactly this works and what are all the different functionalities and different system that it has. So, our only thing is that how do we implement it that we will see. So, we will connect according to our input signal.

(Refer Slide Time: 26:28)



So, what I will do that I take a 5 terminal because the plus V c c and minus V c c are very much important to understand whether it goes to the saturation or not. So, that is the reason I am taking this value plus V c c and minus V c c too and I will take some voltage sources DC voltage and I want to operate my system with 15 volts changing settings to the input voltage to 15. So, positive is connected to positive terminal and other terminal should be connected to the ground. So, I am connecting it to the ground.

Now, I have to take another voltage source because op-amps has to be provided with a differential difference volt two different voltage sources this is not a single source we have to always take two sources, two independent sources basically. So, the negative of the power supply is connected to the negative terminal. So, since negative 12 since it is the amplitude is 12 since the negative is connected here the value is 12 minus 12 volts. So, since we require minus 15. So, this does are required. Now, what we have to do we have to connect one resistor at this point. So, in order to in order to have a mismatch between both the this as well as our design in multisim what I will do is that this is R 1 I will consider and this I will say 100 k.

In fact, you can also take any resistance value, but it should be all resistance whatever we use should be same one same one, but higher the resistances right more the input impedance of the system; more higher the resistances more noise into the system noise is always proportional to the resistance value resistance (Refer Time: 28:40) excuse me. So, that is a reason we have to moderately select between 100, 10 k to 100 k, but 1 k if I select is even we can select one k, but it will have slight loading effect to the previous stage of your system loading effect on the previous stage of your system if I go more than 1 k 100 ohms it will have more loading effect on the system. So, in order to not have that we are considering somewhere around 10 k to 100 k.

So, in this case I am considering 10 100 k. So, I need to take one more resistor and this is my R 2. So, this R 2 part is done. So, this part I have to connect it to the ground. So, the ground terminal I have taken I am connecting it here, and this part should be connected to here and this part also connected to the positive term[inal]-. So, this is nothing, but V 1. So, I will take one more DC voltage source connected this point, right. What I will do is that this I will make it as the name of this I will make it as V 4 because V 1 notation we are giving it for the input values. So, this I will make it as V 1.

Now, so, V 1 is ready. So, this value make it to 10 max is of 10 we are looking at. So, 10 other terminal should be connected to the ground. So, I am connecting it to the ground. So, this part is done. What is the other part the negative feedback and the negative resistance at the negative terminal. So, I will take R 3 resistor. So, this is what R 3 that we are considering it and one more resistor that I have to take which is R 4 which should be connected as a negative feedback. So, I am connecting one here one more to this junction and other terminal to the output voltage, right.

So, this point I have to connect another voltage source. So, just a nomenclature just I will just slightly change the naming of the system here. So, this I will name it as a V 5. So, whatever I take will be V 2. So, I will take one more voltage source, this is V 2 voltage source and this part should be connected to the ground connected to ground, ok. So, this I will start from two volts. So, to understand to understand what we have done we have to apply 10 volt 2 volts let me see. First we will see the differential gain then we will we will do the gain of I think we have considered the resistance R 3 R 4 differently and let me do the same experiments once again.

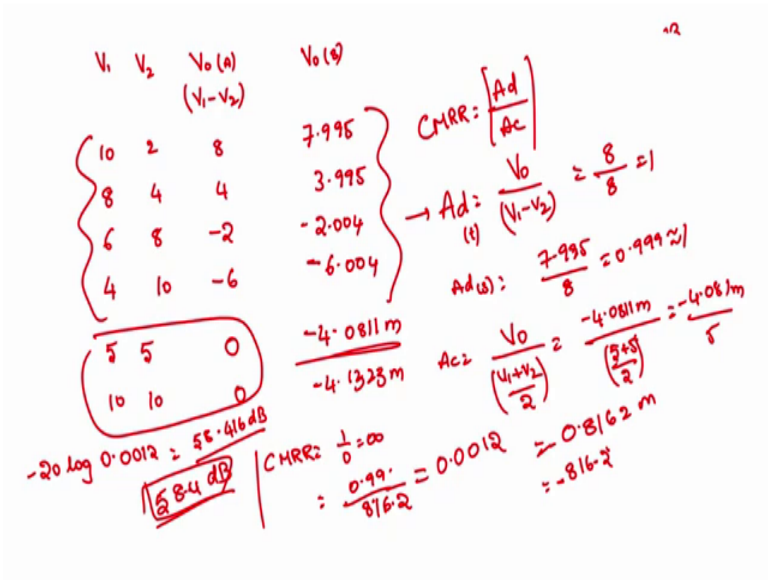
So, I will take V 1 connect it here and this should be ground making it as ground. So, this should start from 10 volts. So, let me take it to 10 volts then I should take one more voltage source. So, I need DC. So, I will take DC connecting it here and this should be ground now. So, we will start from 10 volts and this value at 2 volts. So, what are all values we have considered one is 10 other one is 2 other thing is 8. So, when we see what are all values that we have consider 10, 2, 8, 4 and 6, 8, 4, ten10.

So, we know that this is 8, 10 and 2, 8, 8 and 4 minus 2 minus 6 we will see what values we are getting for everything then we will list it out. So, let me run when I run it we are getting output as 7.9958 whereas, when the input is 8 volt I am making this as 8 and this as 4 volts. So, what is output we are getting 3.995. So, approximately are almost close because we always consider 3.99 as equivalent to 4. So, it is also giving 4. So, let me take it as 6, 6 this should be 6 volt and this value should be of 8 volt 8 volts when I see the values minus 2.0041. So, almost same 0041.

Now, this I will take it as 4, and this I am taking it as 10. So, what is the value we are getting minus 6.0040. So, we got all the values we also take V 1 and V 2 as same values and we will see how much we are getting. So, we will take V 1 as 5 volt one value and V 2 also as 5 volt are the value. So, when V 1 is 5 volt and V 2 as 5 volts actually the actual voltage should be 0, but as I told you it will be always at millivolt. So, when we see it is somewhere around minus 4.0811 millivolt. So, what about for other value? So, let me take the value somewhere around 10 volt and this also at 10 volt should be almost same. Yeah, see when we 10 and 10 actually the value should be 0, but we got minus 4.1323 millivolt.

Now, let me put everything in graph and we will put everything in our slide and let us see how what we get.

(Refer Slide Time: 35:25)



What will be the CMRR value, right and so, when we recall what values we got V 1, V 2 actual output. So, actual output is nothing, but V 1 minus V 2. So, here I will write V 1 minus V 2 no gain because 100 by 100 will be 100 k by 100 k it is it is 0 and consider this is simulation V naught of simulation output voltage at simulation what is the value we are getting. So, V 1 we are consider 10, this is 2. So, what is the value 8 we got, right. When we do manual calculation, this is 8. What about the simulation we got 7.995 volt, then this is 8, this is also 4, this we got 4, so, whereas, this is 3.995. When we apply 6 and 8 as an input voltage we got minus 2 even here we got minus 2.004.

What about here 4 and 10 we got minus 6 when we calculate theoretically and simulation we got 004 minus 6.004 and we have also done other experiments when both inputs are same which are nothing, but common mode signals, but actually speaking the output should be 0, but we are not getting 0 we are getting some value of 0.811 milli and even it is almost same even when I am I am when I am taking different voltage value of 10 and 10 which is of minus 4.1323 milli.

Now, if I want to calculate CMRR; CMRR first I should know the calculation of differential gain, then I have to calculate common mode gain, but how do differential gain? So, the differential gain is nothing, but output voltage that we are getting divided by common mode signal sorry divided by differential input signal V 1 minus V 2. Now, when we see the theoretical value, so, this is 8 for the first one and 8, this is 1. So, we are getting differential gain as 1, right. So, even for the second case 4 divided by 8 minus 4 4 1. So, whatever no matter what for this particular set of values we will get the gain as one theoretically. What about the practical? This is theoretical.

So, Ad simulation when we see the value is V naught. V naught is 7.995 divided by 10 minus 2, 8. So, when I calculate I am taking calci 7.995 divided by 8 0.999 which is almost equal to 1, no matter what I will take the next value too, I will calci. So, 3.995. So, 3.995 divided by 8 minus 4, 4 0.998 so, almost equal to 1, right we are getting almost everything equal to 1.

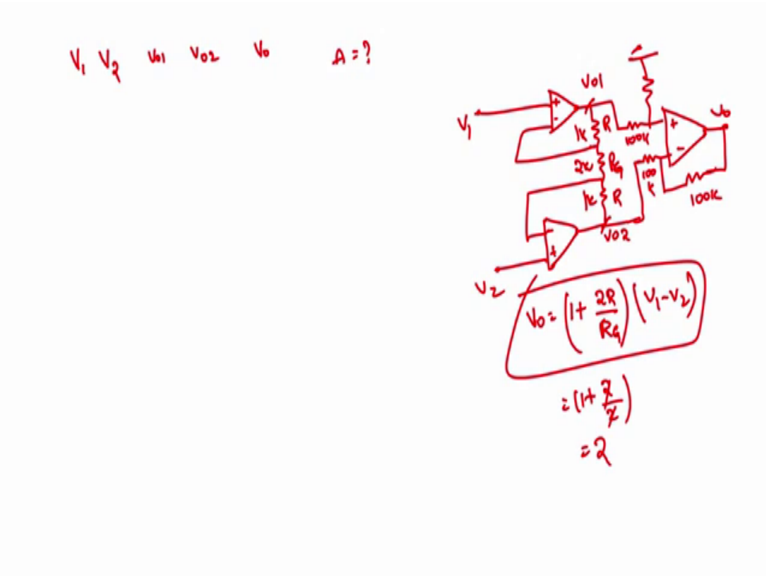
Now, what about Ac theoretically it should be 0, but practically when I see simulation was when I see the value is minus 4.0. So, how do we calculate first let me write the formula output voltage by common mode signal. So, V 1 plus V 2 by 2. So, what is V naught minus 4.0811 milli divided by 5 plus 5 by 2? Which is nothing but 10 by 2 again this is 5, so, minus 4.081 milli divided by 5. The value is and I take a calci 4.081 divided by 5, point 0.81 how much 62 milli 0.8162 milli. So, that means, the value is 816, no volt because volt by volt will be cancelled, right 0.816 milli or 816.2.

Now, if I want to calculate CMRR. CMRR theoretical when I see it should be ad by ac one divided by 0 which is infinity, but practically is it the same let me see which is differential gain which is of 0.999 or 998 or 0.99 divided by 81 816.2. So, the value is let me take a calci 0.99 divided by 816.2 which is 0.0012.

Now, I if I want to calculate in dB 20 log 0.0012. So, I will write it down here itself 20 log 0.0012 which is equal to. So, I will take calci once again 0.0012 log into 20. So, which is 58.416 416 dB. Why I am not why I am eliminating minus because same error should be always mod off or even in this case here we have a negative and when we calculate minus we are getting minus is becoming positive, but CMRR generally mod of Ad by Ac. So, which is 58.4 dB for this particular type of op-amp right, right.

Suppose, if you are taking different op-amp I do not know what op-amp that we have considered in the simulation what make that we have considered. So, we have simply used the op-amp that is available there, right. So, this is how we generally calculate the dB of our differential amplifier, but moreover since we are not going to apply almost common mode signal, but even if we apply we are getting somewhere in the milli since it is negligible. So, we can simply go with a difference amplifier itself. Now, how about for instrumentation amplifier why do not we look into that? So, what I will do is that I will take one more slide for a instrumentation amplifier.

(Refer Slide Time: 42:57)



If we recall the working of an instrumentation amplifier, so, it will somewhere will be taking three op-amp plus minus one more op-amp plus minus right resistor combination. So, this is R, this is R, this is R g if I take minus and plus connecting here this here and this here if I say this is V 1 this is V 2, right and I should also have to have a differential amplifier plus minus, oh sorry this is R g the output should be connected one here one more here and one more here one more here. So, 100 K 100 K 100 K over resistance here 1 K 1 K if I take the V naught. So, when we see V naught is nothing, but 1 plus generally V naught value is 1 plus 2 R by R g into V minus V 2 is the equation just look into the instrumentation amplifier circuit you will understand.

Now, in this case what we do is that we will design the same thing and we will see for different values of V 1 V 2. Now, I will say this is V o 1 this is V o 2. What are the values of V o 1 we are getting, what we are getting for V o 2 and what about V naught. So, I will take R g as 2 K. So, if I take R g as 2 K the gain will be 1 plus 2 into 1 K divided by R g 2 K. So, this is this one. So, the gain is 2, right the gain of the system is 2. So, we will see what is the gain of the system even theoretically it and so, theoretically we have calculate which is 2 we will see with simulation.

Now, so, to the same circuit what I will do is that I will take few more op-amps. So, let me keep this aside I will take simply three terminal op-amps it is more than enough, ok. So, I have to chose different resistors one here one more here and one more here. Now, the output has to be connected at this point and negative terminal should be connected here this two here and this two here whereas, the negative terminal should be connected here this is my V 1 whereas, this is my V 2 this is to be connected.

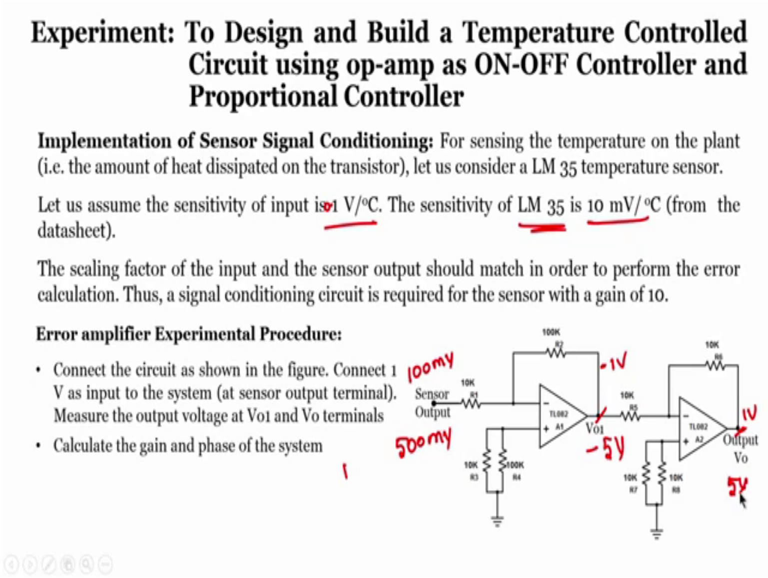
So, all the required connections are made let me run. So,. So, this is V o 1 this is V o 2 this is V naught. So, I will take two more probes connect at this point one more probe at this point which gives you V 1 when I run it, yes. So, when we see both are at 10. So, we are getting 4 point minus 4.1323 milli. So, let me change 10 and 2 10 and 2. So, so 10 and 2 how much we are getting at this point we are getting 12 this point we are getting minus 3.0158, ok.

Now, I will see. So, V 1 V 2 V o 1 V o 2 and V naught V 1 is 10 V 2 we are where applying 2 V 1 we are getting 12 and V o 2 is minus 3 V naught is 15, right. So, 10 minus 2 is how much 8, 8 into gain of 2, 16, approximately 15 we are getting because why 15? It has gone to the saturation because of the voltage. So, what I will do is that I will decrease 2, 4. Now, second inputs 10 and 4, 10 minus 4 is somewhere around 6, 6 into 12 I should get an output of 12. So, we are getting 12.056, right.

Then, so, this I will this I will increase 8, this V 2 to 4 let me take this as 8 and 4. So, 8 minus 4 the theoretical value should be 4 and 4 into 2 so, but we are getting 11.0996 sorry 11.996. Now, what I will do is that V 1 I will make it as 4 V 2 as 8 this to 4, this I will make it as 8. How much we should get 4 and sorry 8 and 4 4 and 8 we got minus 12.004. Let me apply the same signal which is of 4 and 4 or 5 and 5 because that is a signal that we have used 5 and 5. So, I got somewhere around when I apply both 5 and 5 I got minus 4.0811 milli.

So, this way we can even construct instrumentation amplifier and we can calculate our CMRR value for the instrumentation amplifier, right. Now, we will see what is our actual thing, right. So, we have we have calculated and theoretically we got the gain of 1. So, theoretically as well as we got practically we got gain as 1 and CMRR as 58.4 dB. So, now, problem with this dB for us. So, we can go ahead with this instrument differential amplifier too.

(Refer Slide Time: 50:19)



Now, now what we will see once we get error signal, right once we get an error signal one another important to get an error signal is output from the sensor, right. So, output from the sensor in this case is you know LM 35. As you already know why we are using LM 35 as we have already discussed we also discuss about the sensitivity the sensitivity of LM 35 is 10 milli volt.

But, the input sensitivity is 1 volt sorry this is 1 volt per 0.1 volt per degree centigrade that is what the sensitivity that we are using. So, so we have to match the input sensitivity with LM 35 sensitivity. So, that both factors will be of same unit in order to match with that we have to multiply the output of the sensor which is LM 35 to a gain of 10. Now, that means, we have to amplify the sensor LM 35 sensor output to gain. So, that it will be my feedback signal.

So, in order to do that you can go with different things, but only thing is that input impedance and output impedance should be properly the loading effect should be properly carried out as well as well as the output should be of same phase, right. So, in this case the whole idea is we have to get a gain of 10. Now, if I if you see this system. So, when we recall this system how does it look like this is our inverting amplifier and this is our another inverting amplifier now when we see this inverting amplifier. So, how do we calculate the gain of inverting amplifier just recall our inverting amplifier circuit when we see that the gain is calculated as R 2 by R 1 in this case.

So, R 2 is 100 K R 1 is 10 K. So, the gain of the system is 10. So, that is what we require, but what is this input inverting input. So, that means, if I apply 10 milli volt here I will get 100 minus 100 milli volt right, but what I require I require plus 100 milli volt, so that the sensitivity will always match. Otherwise there will be a phase difference because we are implementing error detector. Suppose, if we implement a summation here if I get a negative so, there some are so, finally, we will get a difference between V 1 and V 2, but we are not doing that, right we are implementing a differential amplifier there. So, that is the reason the phase output should be in positive, right.

So, in because of that reason the output of the inverting amplifier output first is of inverting amplifier circuit has been connected to the second stage of an inverting amplifier with a gain of one. So, since a gain is 1. So, no change in the amplitude output voltage, but there will be a phase because it is also a inverting. So, we will get output as 100 milli. So, now, problem solved.

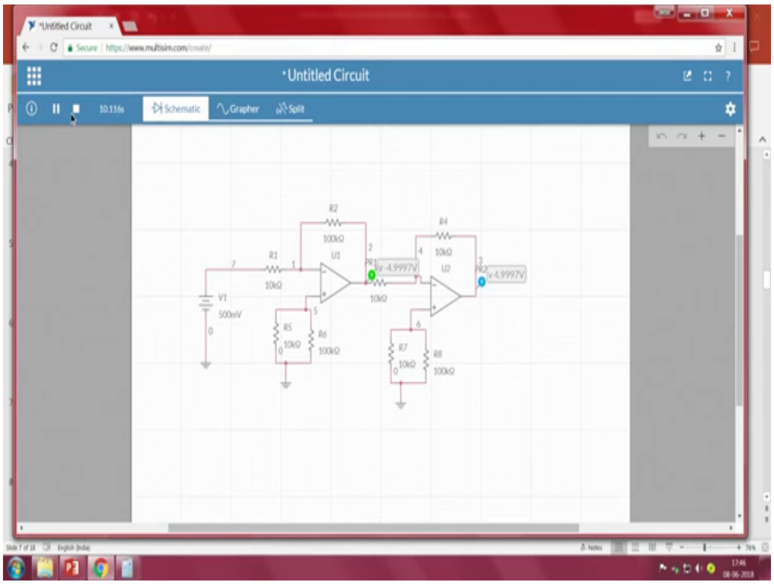
But, is this the only way to do? No, we can also choose non inverting amplifier, right with 20 K and 2.2 K resistors. So, when we calculate the gain will be approximately equal to one 1 plus 9.08 which will be 10.08 approximately equal to 10 K 2, with a single op-amp also we can do, but I have chosen in this way. So, it is not compulsory that you have to always go with the same (Refer Time: 54:12), but only thing is that it should provide us the gain of 10.

Now, what is the reason behind taking this resistances here? So, when we recall if we recall our previous module discussions we told that the requirement of no, the resistance at 10 K and 100 K are for offset, sorry bias currents compensation, right. So, to compensate for the bias current of an operational amplifiers if I connect R 2 and R 1 in parallel. So, it can be completely compensated. So, that the reason whatever the resistors that we are choosing here R 1 and R 2, the resistors have been connected in parallel. So, that it is also compensated for the bias currents too.

Now, we will see whether it is giving as a gain of you know 10 or not. So, for that case what I will do is that first I will take sensor input as 1 volt right. So, since it the gain is 10 we will go with the millivolts itself I will take 100 mili. So, theoretically when we calculate we will get minus 1 volt here I should get 1 volt. Now, I will take 500 mili right, gain is 10 theoretically we should get minus 5 volt and here it should be 5 volt. Now, why do not we create a circuit in simulation and verify it?

So let me go back to the simulation, right and new file let me save this. I am taking a new file.

(Refer Slide Time: 56:34)



Right, I will take an op-amp right. So, two op-amps in our case. So, both the op-amps. Now, we have one resistor this resistance we have considered as 10 K. So, let me change into 10 K this is 100 K I have considered 100 K. So, let me connect the wiring from here to here to here and these resistance we have considered as 100 10 K and 10 K. So, I will take 10 K resistor one connect here one more 10 K here.

Now, for compensating the bias currents what we are doing we are also taking the resistors whatever we have chosen in parallel, right. So, I have taken even the parallel connection of the resistances connecting it here one pair. So, I also need one more pair. So, and this pair has to be connected to the ground. So, as connected to the ground. So, I will copy everything and paste it here this has to be connected here, right. So, both the parts are done.

Now, now this is my input to the system that is nothing, but the sensor output has to be connected here. So, consider as a voltage source, DC voltage connecting it here and other terminal to the ground. So, we told we took 10 milli, 100 milli the reason is that more than that suppose if I take 1 volt gain multiplied by 10 it will become 10 volts it may go to the saturation almost close to saturation where I cannot apply any other thing. So, that is why I am taking 100 milli 100 millivolt. So, let me measure the voltage at this point as well as at this point. If we recall for 100 milli the gain is 10 we will get we should get output as minus 1 volt let me run minus 999.4 millivolts which is minus 1 volt.

Now, after passing through another operational amplifier which is phase changer so, the negative has become positive. So, this is working fine. So, we will take another one 500 milli we should get sorry 500 milli right minus 4.997 plus 4.997. So, that means, it is giving the complete system the signal conditioning circuit whatever we have designed for LM 35 sensor is having a gain of 10 and having the same phase, so that we can directly the output from the signal conditioning circuit can be directly connected to the error amplifier.

So, we have seen this part signal conditioning as well as differential. So, we finished this part and this part. Now, we will see the working of the heating circuit or the plant then we will look into the controller part. Once everything is done one by one we will see the breadboard or the PCB board that we have created for the complete experiment we can see how exactly this working and finally, we will demonstrate you the controlling output based upon the system input.