Op-Amp Practical Applications: Design, Simulation and Implementation
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Lecture – 25
Design and Development of Temperature Controlled Circuit using Op-amp as ON-OFF, Proportional and Proportional Integral Controllers: Introduction

Hi, welcome to this module and in this module what we will learn we will learn how to design and build a temperature controlled circuit using operational amplifier as an ON-OFF controller and proportional controller. So, how can we develop a temperature control circuit? So, now where exactly you find this kind of circuit? You find this kind of circuit in many applications.

So, let us see how we can design this circuit and then we will see what application we have thought of.

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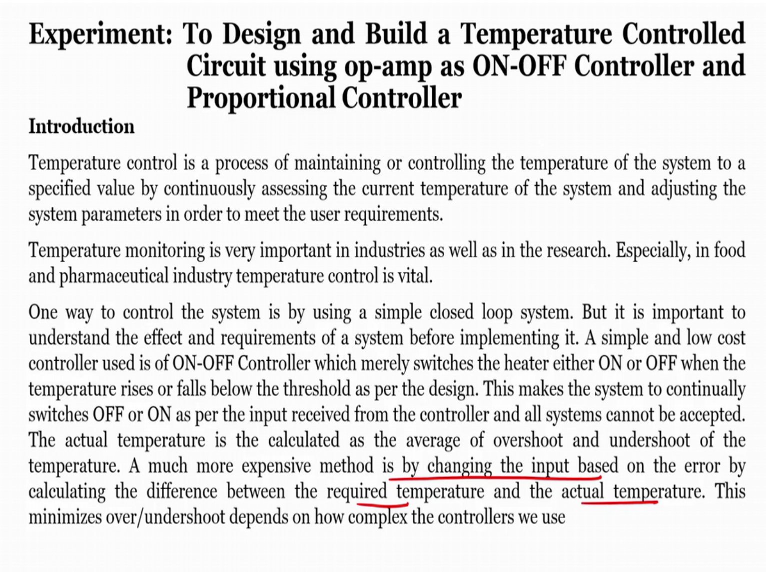

So, to start with if you see the slide the temperature controller is a process of maintaining or controlling the temperature of a system to a specific value specified value by continuously assessing the current temperature of the system an adjusting the system parameters in order to meet the user requirements. So, what we can see? It can be used for air conditioning system, it can be used for AHU's, it can be used for the in the industry applications, lot of applications are there for temperature control circuits.

Now, in particular industries temperature monitoring is very important and when we talk about research laboratories, it is as equally important like industries in a research laboratories as well. So, when we talk about pharmaceutical industry or when we talk about food industry a temperature control is extremely vital, is extremely important, right.

So, how to designed a temperature control system? So, the first ideas that to our mind is to use a simple closed loop system, but it is very important to understand the effect of requirements of a system before we actually implement it, right. So, a simple and low cost controlled used is off is ON-OFF controller which merely the switch is the heater either ON or OFF when the temperature rises or falls below the threshold as per the design. So, the easiest way to design is this to design on off controller. So,, but in that case the what happens the these makes the system to continuously switch is ON and OFF, right. In ON and OFF of controller what happens? The system continuously switches between ON and OFF states.

So, when you see that the what you see in this slide you see that when you do that the actual temperature of the is calculated as the average of overshoot and undershoot of the temperature much more expensive method is by changing the input bias on the error by calculating the difference between the required temperature and actual temperature. If you know the required number if you know the actual temperature then you can understand the difference and minimize the overshoot and undershoot depending on how complex we can use the controllers or how complex controllers we can use.

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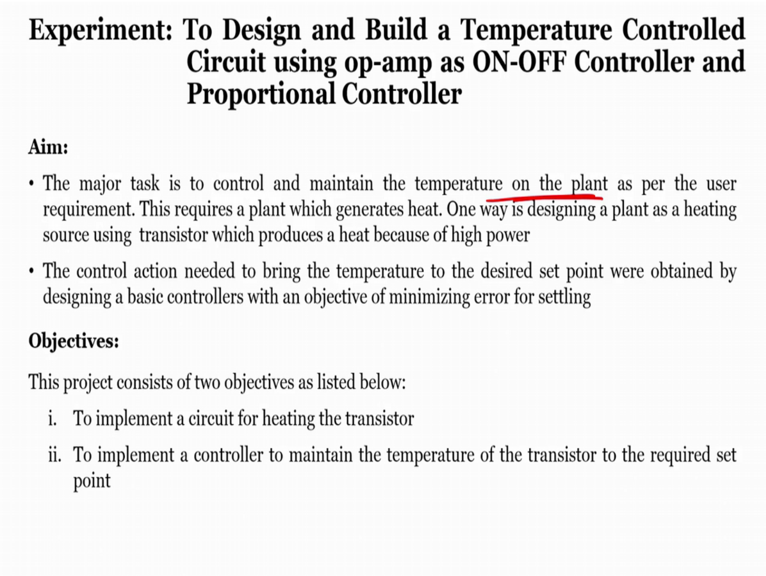

Now, the aim of this particular experiment is the major task is to control and maintain temperature on the on the plant, right as per the user requirement this is our aim one. This requires a plant which generate heat one way is designing a plant as heating source using transistor which produces heat because of high power, right. Second is the control action needed to be bring the temperature to desired set point which will be obtained by designing a basic controllers with an objective of minimizing errors for settling.

Now, what are the objectives? The objectives are first is to implement a circuit for heating of the transistor and second objective is to implement a controller to maintain the temperature of the transistor, right. So, let us see how we can do that.

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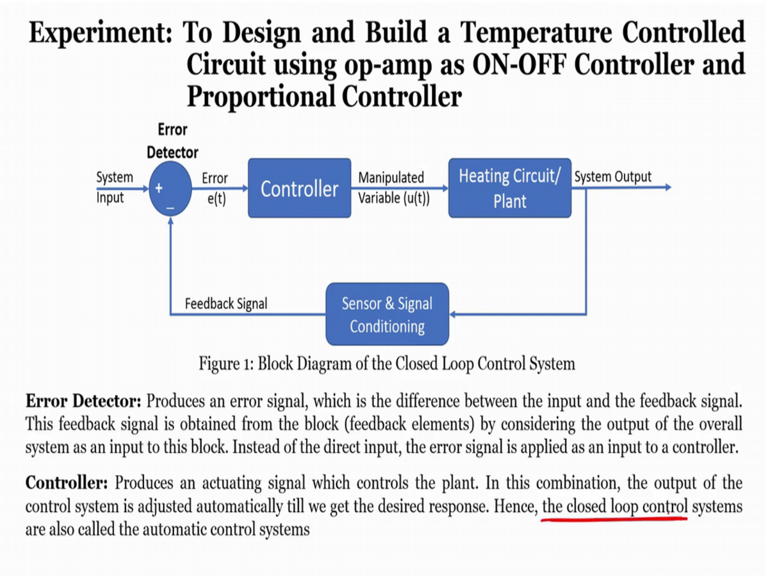

Now, this the block diagram of the closed loop control system where you can see the system input is given to the error detector and the based on the system input in the feedback signal the finally, whatever the error is there that is feed to the controller, right which is further manipulated by and you can assume that a variable u t's is applied to the heating plant right based on that the either the circuit will heat or it was shutdown there is on or off and the temperature at the output is measure which is again feedback to the sensor the signal conditioning circuits; that means, the sensor and signals signal condition circuit consists of that the temperature sensor, right and if the if the temperature is higher than what is the set point right then that kind of feedback signal is given and if the temperature is lower, then according to that the feedback is given to the error detector. So, the point is our error should be minimized that is the idea, all right.

So, now, what is the role of error detector error detector produces an error signal which is the difference between the input and the feedback signal. This feed signal is obtained from blocks which are feedback elements by considering the output of overall system as an input to this block, correct. So, instead of direct input the error signal is applied as a input to the controller, right. Instead of directly we applied system input we apply the error that is the difference between system input and the feedback signal.

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Now, what your controller consist of? Your controller consist of or it actually the system which produces an actuating signal which controls the plant the combination the output of the control system is discharge automatically till we get the desired response, right and hence the closed loop control system are also call the are also called as the automatic control systems, right. So, we can also called it is a closed loop system or we can also called as an automatic control system, right is very easy.

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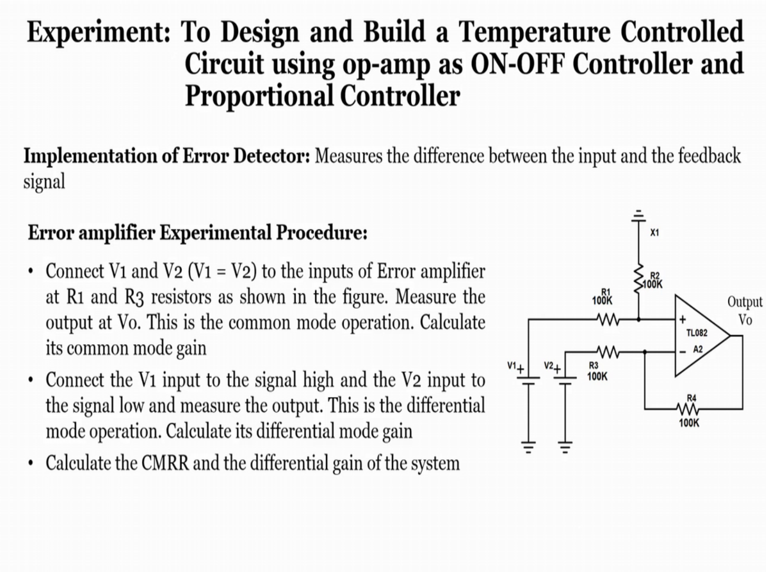

Now, the implementation of error detector that is the measures the difference between input and the feedback signal as we are discussed, right. As a error amplifier experimental procedure you see this is a circuit ok. So, what we are do? Connect V 1 and V 2 such that V 1 equals to V 2 the input of the error amplifier, right. So, the V 1 equals to V 2 and that is sent to the input of the amplifier, correct? Now, measure the output voltage V o, this is your common mode operation, right.

Now, connect V 1 so, let us do the second part and second part what we do and actually we will see this thing also in the experiment,. We will see in the experiment class the how to design this particular temperature controller circuit. So, the second one second part of this experiment is connect the V 1 to high signal and V 2 to a signal which is low and measure output. If there is a difference, right so, there is a differential mode gain and finally, we can calculate CMRR and a differential gain of the system. You know that CMRR is nothing, but the ratio of differential gain to common mode gain, right.

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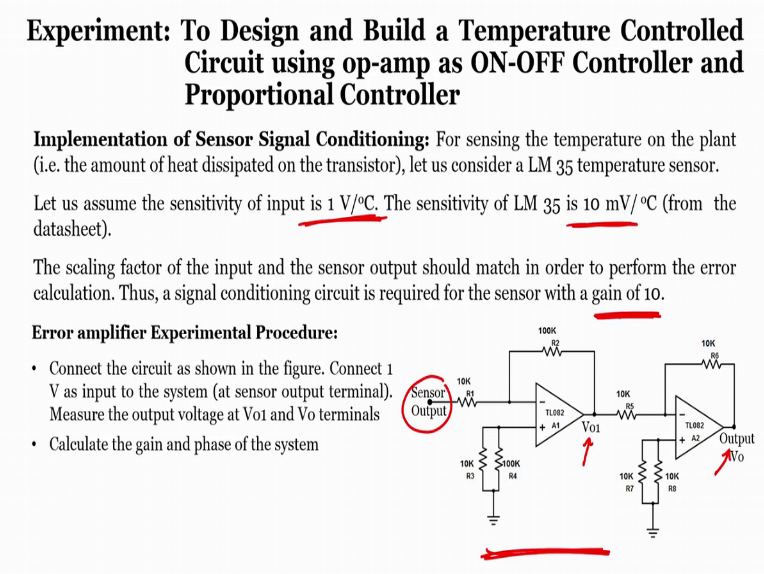

Now for sensor signals conditioning circuit; how to implement that? for that, we have the temperature of the plant that is amount of heat dissipated of the transistor let us considered as LM 35 temperature sensors. So, we will use LM 35 temperature sensor for implementing our signal conditioning circuits and let assume the sensitivity of the input is 1 volt per degree centigrade, that is our sensitivity. Now, the sensitivity of LM 35 is 10 millivolt per centigrade. Now, from where we get this LM 35 is 10 millivolt per degree centigrade? We can get from the datasheet.

This scaling factor of the input and sensor should match in order to perform the error calculation. Thus is a signal conditioning circuit is required for sensor with the gain of 10, right. You can see that sensor output and the input right scaling factor should match and for that in this particular condition we require amplifier or a signal conditioning circuit with a gain of 10.

Now, for the error amplifier procedure what we will do we will connect the circuit as shown in figure one or we this particular figure let us say if this figure it is not figure number one just a figure, ok. Now, connect one 1 volt as a input to the system, right that is at sensor output here 1 volt and measure the output at V o 1 here and V o and you have to do you have to calculate the gain and phase of the system.

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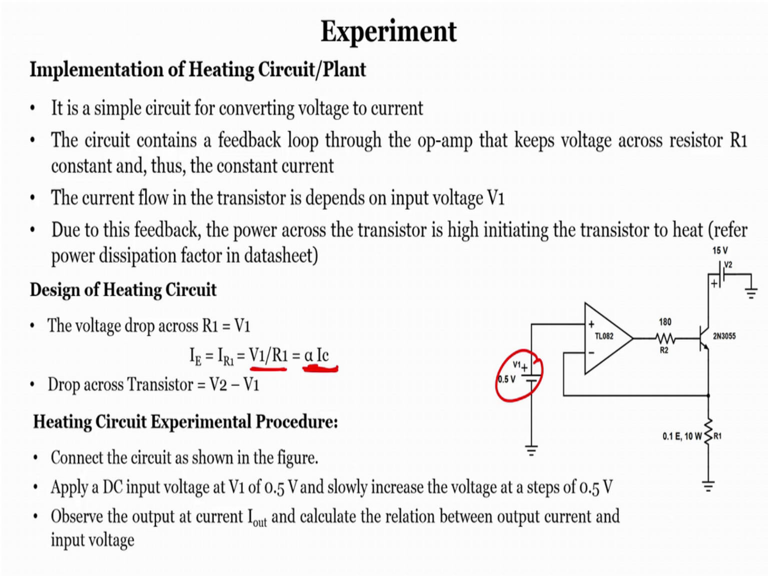

Now, for implementing or implementation of heating circuit or plant, it is a simple circuit for converting voltage to current circuit contains a feedback loop through op amp that gives voltage across resistor R 1 constant and thus the constant current, right, this is the circuit. The current flow in the transistor is depending on the input voltage right because whether transistor is on or off depends on what is a voltage that we apply what is the voltage that we apply to this operational amplifier, right.

Now, due to this feedback the power across transistor is high initiating the transistor to heat, right or we can see the heat dissipation in the datasheet. So, designing of this circuit would be the voltage of across R 1 will be nothing, but equal to V 1. Now, if I E equals I E is your current flowing through emitter is equal to I R 1 right is equal to you can say I E is equal to I R 1. Now, where is I R 1? I R 1 is V1 by R 1, right V 1 by R 1 or you can say is equals to alpha time I c which is the current through the collector. Now, drop across transistor is nothing, but V 2 minus V 1, V 2 minus V 1, all right. So, that it be the drop across the transistor.

So, for heating circuit experiment the procedure is you can connect the circuit as shown in figure which is write over here and apply a DC input voltage V 1, right 0.5 volts and we slowly increase the voltage a steps of 0.5 volts and for that we observe the output current I out and calculate the relation between output current and input voltage there is a procedure for the experimental part.

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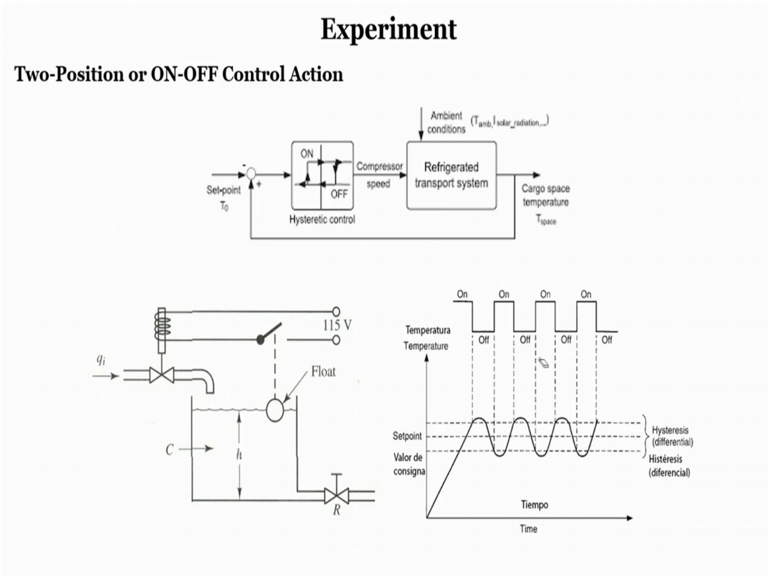

Now, let us see two-position ON-OFF controller. Here what we see is again this is a same thing is the hysteresis control the compressor or speed and refrigerated transport system. There is a ambient condition that we have to take into picture and then there is a cargo space temperature. This is a feedback given to the error. Like I said that this is set point on at which we want to have the temperature of the system and whenever the error is there based on that the error is feed to the hysteretic control.

Now, this is another example where you can see the two-position control system, right? right over here and this is the plot where we can see that what is our set point, right, what is the designed or designated value and what is the hysteresis differential, right. At the same time how the temperature will controller will work it will switch on and switch off when they said it is about set point right about set point you can see here the switch is off when goes go below set point here the switch is on. So, this ON-OFF action is continuous whenever the set point the temperature is below the set point or above the set point we can we can start or we can work on the ON-OFF control action of the circuit, right.

So, if you go to the next slide what we find?

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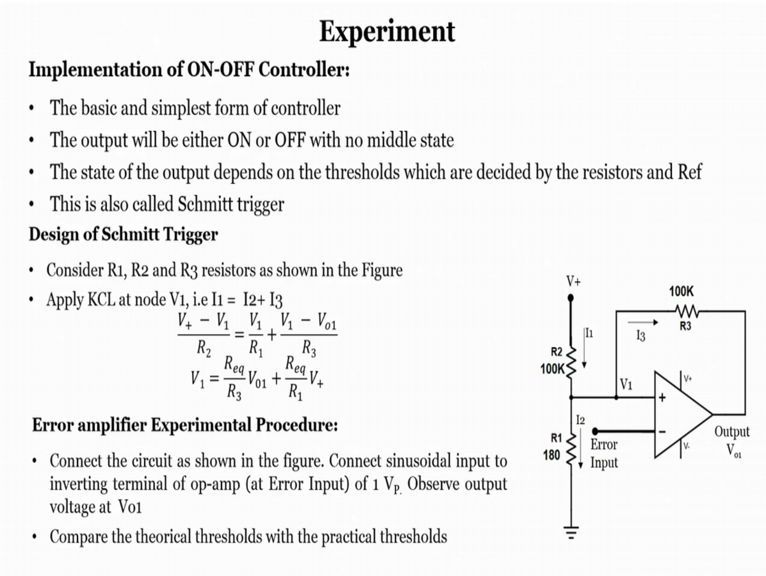

That, if you want to implement this ON-OFF controller, then the basic and simplest form of controller, this is ON-OFF controller or basic and simplest form very easy to design. The output will be either ON or OFF and there is no middle state. The state of the output depends on thresholds which are decided by registers and reference. This is also called Schmitt trigger. We have seen Schmitt trigger circuit earlier as well, like I said we assume we have since Schmitt trigger which is inverting Schmitt trigger we since Schmitt trigger which are non inverting Schmitt trigger.

So, now if we consider R 1, R 2 and R 3 is resistors as shown in figure which is right over here, right R 1, R 2 and R 3 and if we apply Kirchhoff current law which is KCL at node V 1, here right here, then what we get we get I 1 this current flowing to R 2 is equals to I 2 plus I 3. So, now, if the substitute value of I; I is V by R. So, I 1 is V plus right minus V 1 by R 2 equals to what is our R I 2. I 2 is nothing, but V 1, V 1 which is voltage over here right and it is here. So, V 1 by R one plus what is I 3 I 3 V 1 here right now we have output voltage V o. So, there is a difference here. So, V 1 minus V o 1 divided by R 3, correct.

So, if we if we equate this then what we have? We have V 1 equals to are equivalent by R 3 V o 1 plus R equivalent by R 1 into V plus. So, how to perform this particular experiment or what is the procedure experimental procedure for implementing an amplifier? Then the first thing is you have to connect the circuit as shown in figure which is right over here and I connect sinusoidal input to inverting terminal of the operational amplifier which is error input and let us say it is 1 volt peak to peak and we can observe the output voltage V o 1 at the output of the amplifier. Same way when compare the theoretical thresholds with the practical thresholds. So, we need to understand the how can implement the error amplifier.

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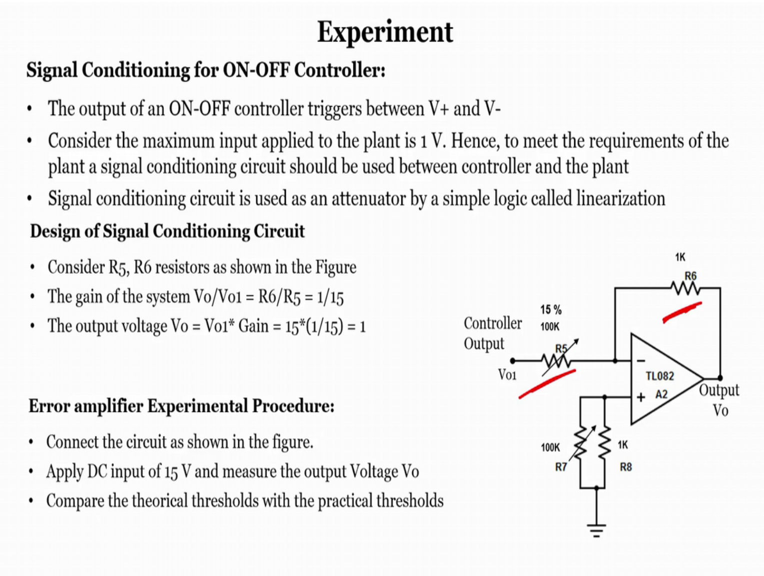

Now, the next one would be signal conditioning for ON-OFF controller. So, we can design signal condition circuit. So, the first thing is the output of an of an ON-OFF controller triggers between V plus and V minus, ok. So, the output of the ON-OFF controller triggers between V plus and V minus we know that right because this ON and OFF state.

Now, consider the maximum input apply to the plant is 1 volt. If I apply the maximum input up to the plant which is 1 volt so, hence to meet the requirement of the plant a signal conditioning circuit should be used within controller in the plant, we also know that, correct. Now, signal condition circuit is used as an attenuator by simple logic called linearization. So, if you want to design a signal conditioning circuit what we can do? We can consider R 5, R 6 registers as shown here which is right over here and right here, right and if you see it is gain is 1 by 15, 1 kilo volt 15 100 kilo ohm and is 15 percentage 1 by 15. The output voltage V o is V o 1 into gain which is 15 into 1 by 15, right and which is equal to 1. So, if you want to design the error amplifier you can connect the circuit applied DC input 15 volts and then you can measure the output, compare the theoretical with practical threshold, is similar to the last slide.

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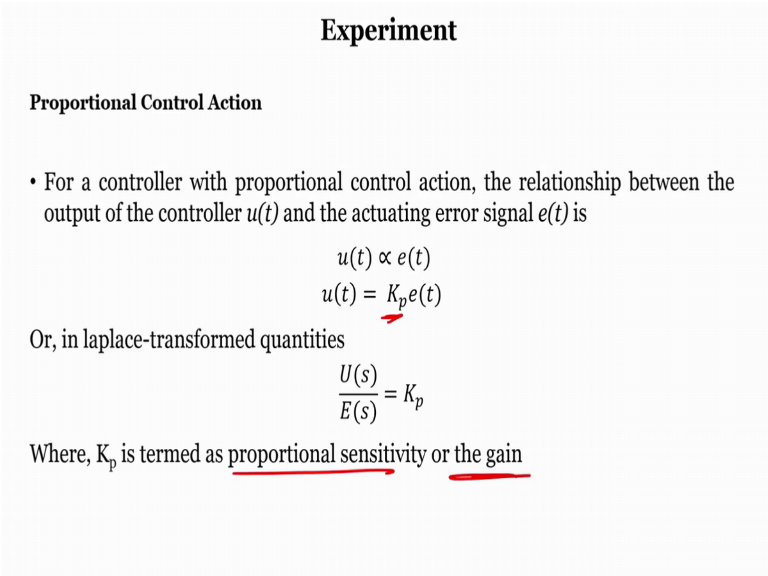

Now, this is about ON-OFF controller. ON-OFF controller is kind of easiness see a proportional controller action. So, for a controller with proportional control action the relationship between the output controller u t and attenuating error signal is given by u t is proportional to e t, now we know that, right.

So, if I further the further solve this then we can have u t equals to K p e t, where K p can be a constant and or in Laplace transform quantities we can write down U s by E s equals to K p. K p is termed as a proportionality sensitivity or the gain. So, this proportional sensitivity or the gain we can keep it constant we can we can change the gain of course,. So, we can say a proportional term where we use K p e t, ok.

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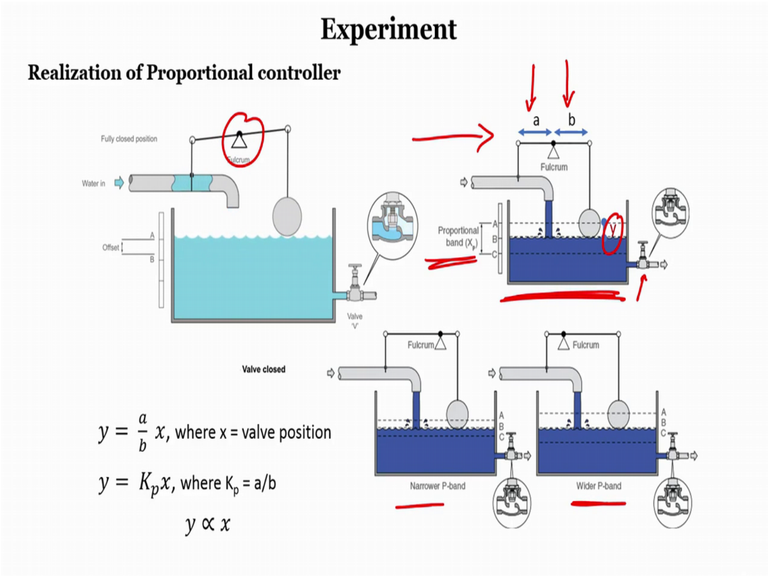

So, now you see this in which we have this realization of proportional controller, right. So, you can see that there is a fulcrum and as soon as the weight. as soon as you open the valve the water goes down and the fulcrum moves this side helping water to fill the tank, right. So, this is the kind of proportional controller um. Same way in this case you understand this is a let us keep in the equation if we keep in the equation you can see here also very simple thing narrow P-band wider P-band, right very easy to understand and then you have here a proportional band which is all the way abc, right.

So, you have three things here. now, first one we have to understand is y equals to a by b x, where x is a valve positions. If you are considered a here, b here and a valve position so, y this y is here. This y is nothing, but a by b into x. So, we can write y equals to K p x, right where K p is nothing, but a by b or we can say y is proportional to x, right. So, very simple example and it is beautifully you know shown in this particular slide. So, very easy to understand you have this a b and you can see that offset signal. As soon as it goes down, this will start filling up and that depends on how you operate the valve. When the valve is closed at the time the tank can be filled, when a valve is open you can see the tank is getting empty dried and based on that the fulcrum would help to open and close the valve from which the water can flow in.

And, the same thing we are this kind of describing in this next figure where we are showing as a and b where the switching of a valve is shown which is like the entry of the water and then the b side is where you if you open this particular valve, then b side would be higher than a and thus we can when we solve this. So, this difference is nothing, but y, right and we if you want to know y then y is proportional to x which is your proportional band, where y is proportional to x and you can also write y is equals to K p x, where K p is nothing, but a by b hm.

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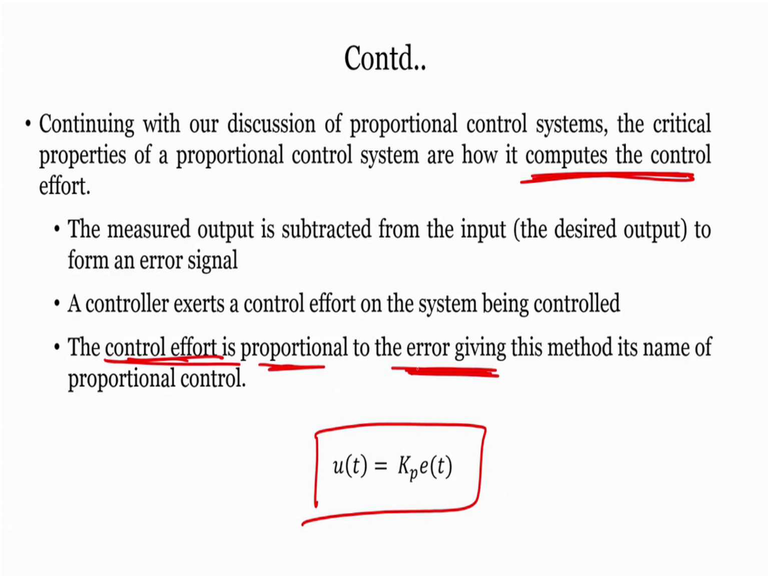

So, now, continuing with our discussion proportional control system, the critical properties of a proportional system are how it computes the controlled effort. This is a very important parameter. The measured output is subtracted from the input to the form an error signal, and a controller exerts a control effort on the system being controlled. The control effort is proportional to the error given and this name that is why this method is called proportional controller, right.

So, this equation u t equals K p into e t, where K p is proportionality sensitivity or gain and the like I say the control effort of proportional controller or weather control effort is proportional to the error given and that is why see is the control effort is proportional to the error giving and that is why this method is called a proportional controller.

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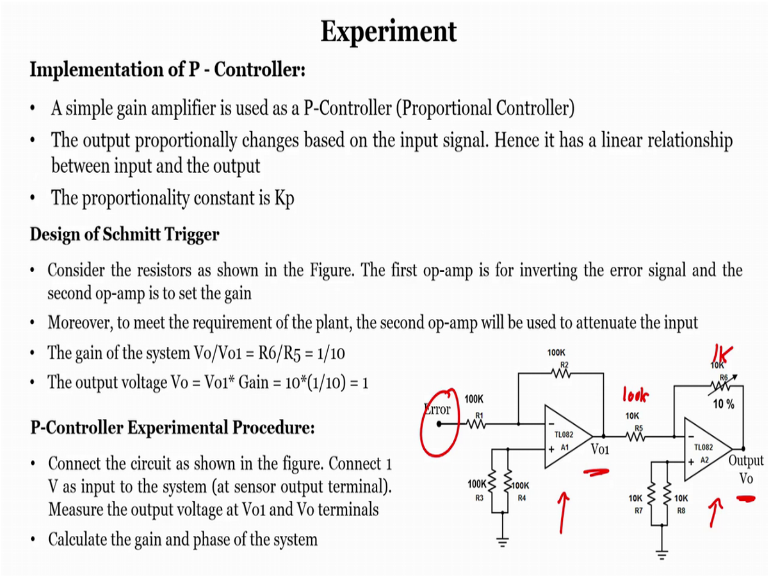

So, if I want to implement the proportional controller what can I do? So, simple gain amplifier uses a proportional controller. The output proportionality changes based on the input signal; hence, it has a linear relationship between input and output. So, proportional constant is K p; like we had discussed earlier it is a constant.

Design of Schmitt trigger: so, if I consider the registers as shown in figure, right I can design a Schmitt trigger very easily. The first op-amp is for inverting of the error signal and the second op-amp is to set the gain, right. So, this one will help us to invert the signal, this one will help us to adjust the gain. The moreover, to meet the requirement of the plan the second op-amp will be used to attenuate the inputs. The gain of the system is nothing, but V o by V o 1. V o by V o 1 equals to R 6 by R 5 equals to 1 by 10, right, R 6 by R 5 equals to 1 by 10 and if I set value of R 6 equal to 1 K right or R 5 equals to 100 K, all right in that can we can have 1 by 10 the output voltage V o is V o 1 into gain which is 10 into 1 by 10 which is nothing, but 1.

Now, for experimental procedure is concerned we can see that we can connect the circuit as shown in figure, we can connect to 1 volt as a input to the system which is right over here and measure the output voltage at V o 1 and V o and calculate the gain and phase of the system. So, this is how we can implement the experiment.

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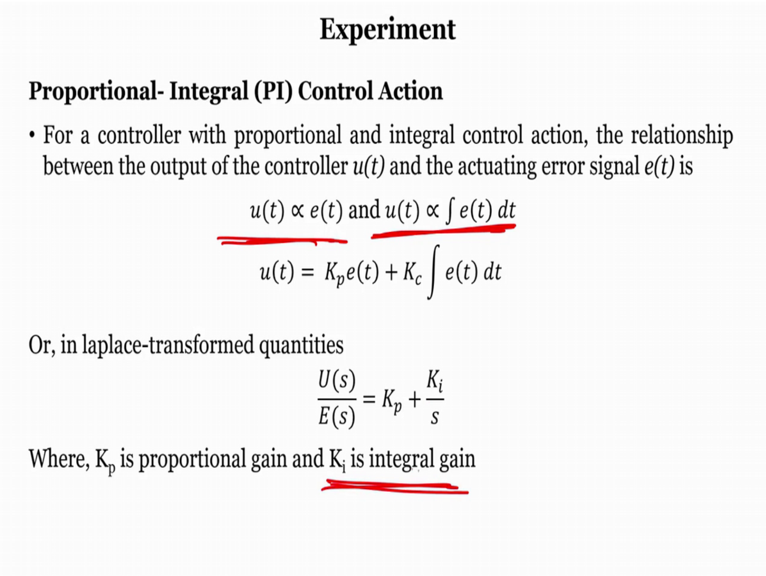

Now, when we talk about proportional how about proportional integral control action? So, for control with proportional and integral control action or a controller that has both proportional and integral action the relation between output controller u t and the actuating error signal e t is given as u t is proportional to e t and u t is proportional to integration of e t dt. So, u t equals to K p into e t plus K c into integration of e t dt.

Now, if you V if you put this thing in from Laplace quantities then we can see that U s by E s equals to K p plus K i by s, where K p is proportionality gain and K i is our integral gain. So, if we have proportional integral controller we can write the equations like this.

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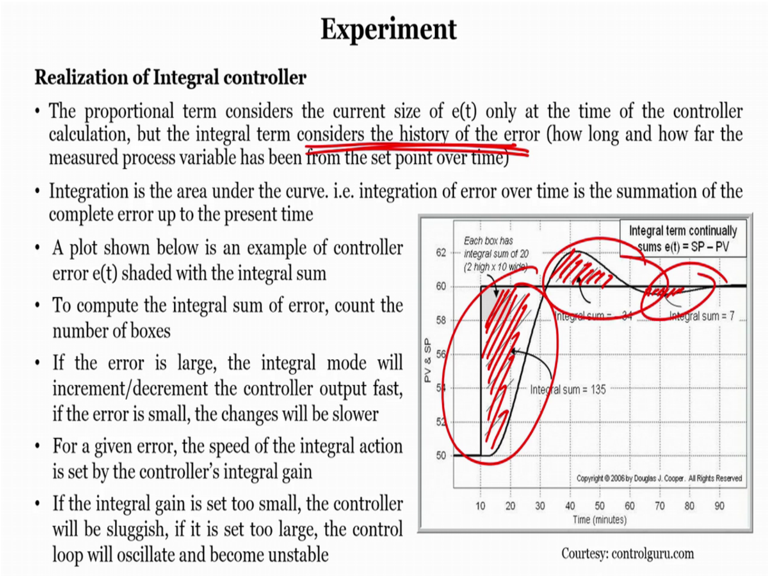

Now, for realization of the integral controller you can see that a proportional term considers the current size of e t only at the time of controller calculation, but the integral consider the history of the error. That is why a proportional integral error controller are better than just proportional controller and there are other controllers called proportional integral derivative which is PID controller which are even more better than PI controller um, but anyway let us continue our integral controller right over here.

So, the proportional term like we discussed consider only the current size of e t and while controlling calculation by the integral considers also the history. So, how long and how far the measure process variable have been from the set point over at time and that is very important for a controller action.

Now, integration is the area and the under the curve integration of error overtime and is summation of the complete and after the present time. We can see here at what is error you can see the area under the curve, same way if there is exceeding our value again the area of the curve, right. So, this will again in this case you can see the area under the curve. So, it is integration of error time in the summation of complete error up to the present time, right. So, a plot which is right over here right and we as we have we are acknowledging control guru dot com because we are taken the platform that particular website. So, a plot shown is an example of a controller error e t shaded with the integral sum.

Now, the idea of our whole NPTEL platform is to help student for teaching and that is why we kind of get the best of the images from possible sources. So, that it is used only for teaching purpose, ok. So, to compute the integral sum of error count the number of boxes, we can do the count and number of boxes and if the error is large integral mode will increment or decrement the controller output and the error is small the changes will be slower, it is very simple.

For a given error, the speed of integral action is said by controller integral gain, right. For can be said by the controller integral gain. If the integral gain is said too small the controller will be sluggish, if it is too large the controller will oscillate and become unstable, correct.

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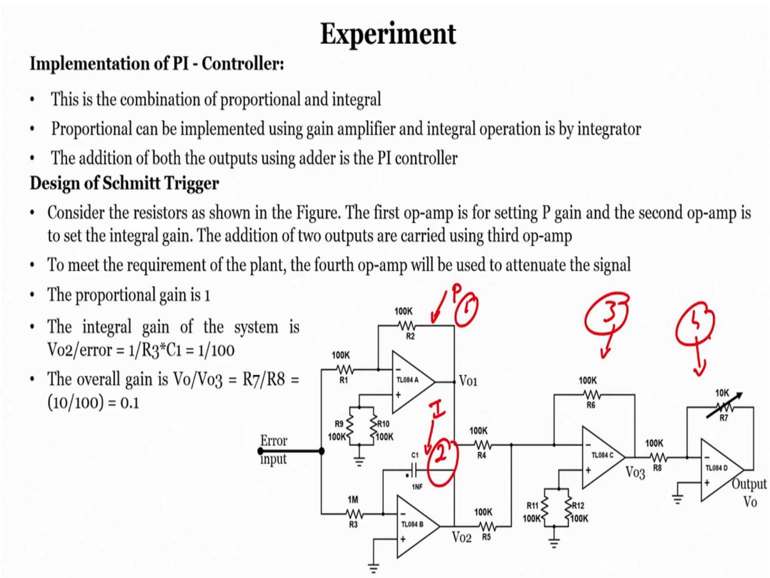

So, that is how things stands, but if you want to implement the PI controller which is proportional integral controller then we know that this is nothing, but a combination of a proportional integral controller. Proportional controller can be implemented using gain amplifier and integral operation is in by integrator, right. So, we have a integrator we can have a gain amplifier and we can further design Schmitt trigger which is consider the registers as shown in figure. The first op-amp is first setting P gain, right which is and the second op-amp is used set the integral gain. So, the first op-amp is used for proportional gain, the second op-amp is for and the addition of two outputs are carried easily in the third op-amp.

So, we can see this is a proportional gain, right, this is the integral gain and the addition of the both is sent to this third op-amp, right let us say op-amp number three, right; addition of proportional integral of output and to meet the requirement of the plant the fourth op-amp will be used to attenuate. So, this fourth op-amp is used to attenuate we can say this is 1 2 3 and 4, all right. So, the proportional gain is 1, now we can see 100, 100 is 1, right. The integral gain of system is V o 2 error by error. So, 1 by R 3 into C 1, which is 1 by 100. So, the overall gain is V o 3, V o by V o 3, correct the overall gain is V o by V o 3 and it is nothing, but R 7 by R 8 which is 10 by 100 which is equal to 0.1, right.

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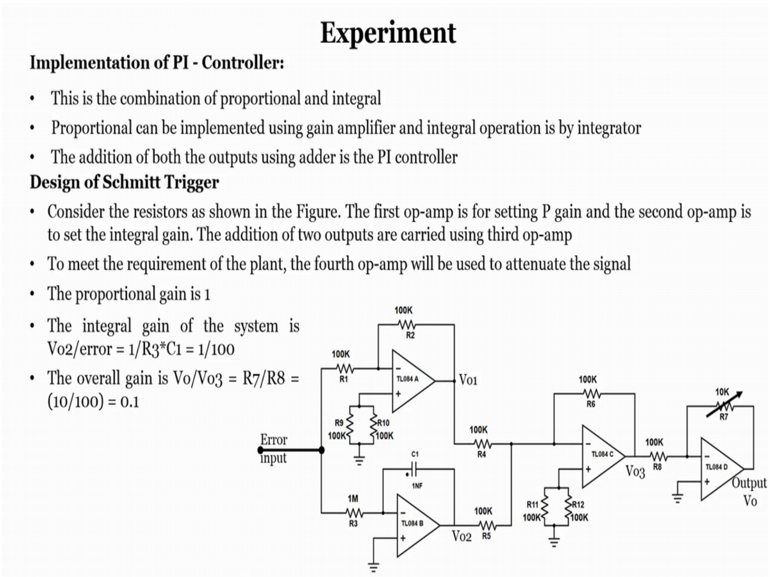

So, now what we have is if we can design the proportional controller, if we can design the integral controller and if we have the third controller third op-amp which is the addition of both and op-amp to attenuate the signal then we can we can design ON-OFF controller using ON-OFF using operational amplifier, the temperature controller using operational amplifier and it uses ON-OFF circuit and it also uses proportional controller as well as integral controller, right.

So, what we have seen here is how to design this particular circuit in terms of we have divided in terms of blocks. So, it is not so difficult when you actually see how you can design or build the temperature controller signal conditioning system, all right. So, that is for this particular module.

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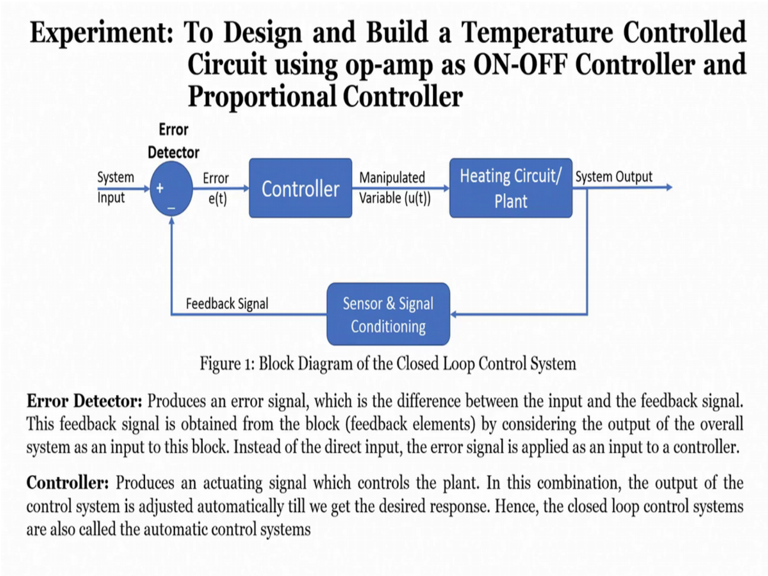

And, in the next module let us see the entire circuit, how we can design, what kind of signals you can generate at the output of every stage and we will see how the controlling temperature of a plant in a real time, right. So, these are all the actual or practical applications of operational amplifier, right. Till then you just look at the slides and I will see in the next class. Bye.