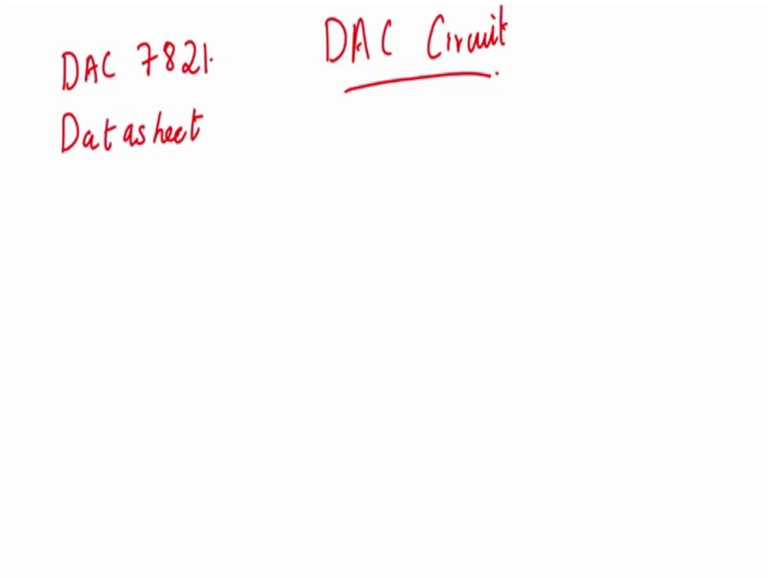
Op-Amp Practical Applications: Design, Simulation and Implementation.
Prof. Hardik Jeetendra Padnya.
Department of Electronic Systems Engineering
Indian Institute of Science, Bangalore

Lecture – 45
Experiments on DAC and its Applications DAC Experiments on TI Board Digitally Controlled Gain Stage Amplifier as DAC Application

(Refer Slide Time: 00:21)



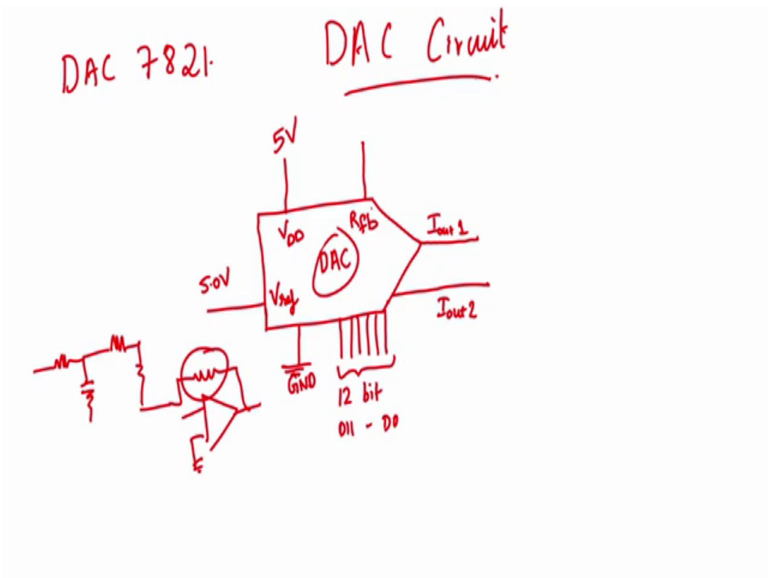
So, we have seen the working of the IC that is used the DSC 7821 IC ok. And we have seen how general DAC circuits work, what is digital domain what is anlog domain what is the conversion from a practical point of view to do the experiment. So, the IC that we are using is DAC 7821 as I just told which is in the board.

So, again I am repeating this board we are just using as just as an EC platform to convey our message of analog circuit design to you. It is not necessary that you need to use the board you can always use this ICs or any other ICs from any other manufacturers to implement the similar functionality that we are trying to introduce to you. It is because of this the reason like we should be equipped to design any type of circuit using similar ICs made by different-different manufacturers. For that only we have we had introduced you to the importance of going through data sheet in the correct manner.

And what should be the exact methodology followed how quickly to go through the datasheet instead of spending hours together in going through the data sheet. How quickly to see the data sheet and arrive at a circuit design implementations so that was the idea with which we have covered these topics.

Now, we have come to something what you can call the grand finale now we will see the exact circuit what we are going to implement and then actually see it on the board after connecting it. And see how digital to analog conversion takes place and how it is differing from the theoretical calculations that we make ok. So, let us see how we can design the circuit our intention also in this course is to make you intuitively design circuits ok. So, just I will show you right now how you can intuitively design circuits ok, let us say so we are taking the DAC.

(Refer Slide Time: 02:19)



So, how it will DAC be so after seeing the datasheet I showed you what are the important signals that you need to look at right. So, let us just show the DAC like this the DAC is shown. So, what are the main things first is ground anywhere for any IC you will have ground so ground will be there clear then what else supply will be there. So, VDD then because it is a digital to analog converter it will have a reference voltage also it is called Vref ok.

Then what is it input anything so this ICs except for oscillators which are self generatory with only power supply they can generate oscillating outputs. Most of the other ICs would need an input here because it is a DAC correct here because it is a DAC we need the input what is the input our input is a twelve bit parallel input digital input correct because it is digital to analog converter so that is D 11 to D down to D 0 ok.

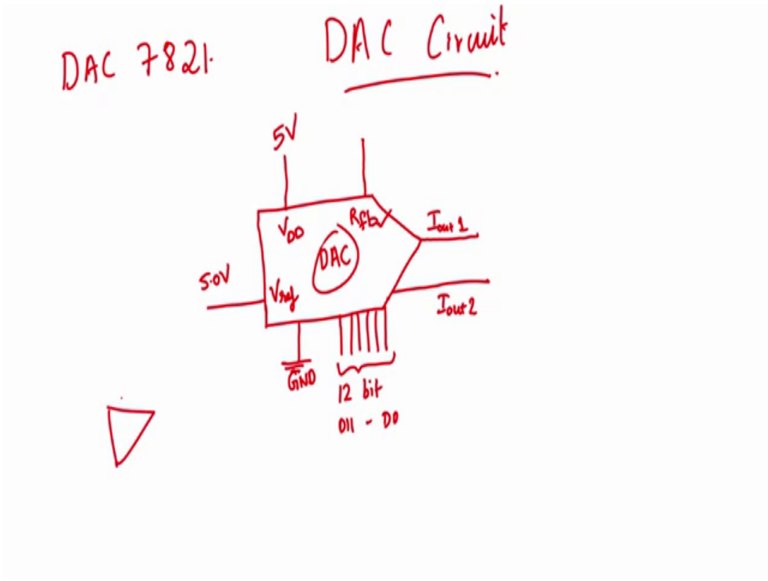
Now, what else is required we know what is the output so output in this IC as we have discussed before is in the form of current. So, we have I out 1 and I out 2 correct. So, what else is there yes you guessed correctly so there is a one more main signal that is for the R feedback R fb ok, so we have made the DAC.

So, now we know the that if we give sufficient supply voltages if we ground it here give reference voltage let us say 5 volt give supply voltage, because this IC works in 5 volt. So, let us say we give supply voltage is 5 volt and then we give input we will we would get some output provided we have given sufficient feedback.

So, what is this feedback resistor? So you have already covered digital to analog conversion in the theory portion. So, you have you might have gone through I will not go to the details of it because this is the practical session. So, you might have gone through the R to R ladder like this so R to R ladder would be there correct; and at the end of it the signals would be amplified using an amplifier right. And there would be a feedback resistor like this that is how the design is so this resistor is this resistor this feedback resistor ok.

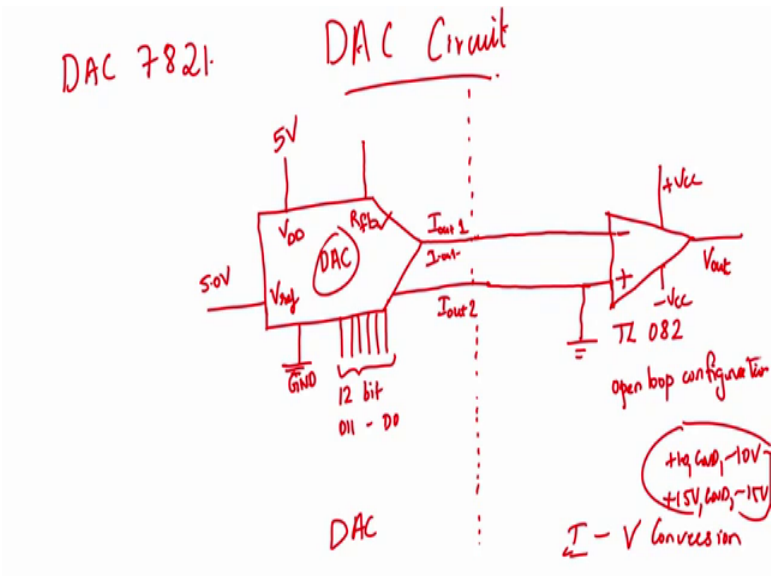
So, but the resister is already inbuilt because it is related to the resistor R to R network this resistor is already inbuilt in the DAC. So you need to only give it to the op-amps output correct.

(Refer Slide Time: 04:58)



Now so most of the outputs be visualize in all circuit design we visualize as voltages correct and this IC is giving us output in the form of current. So, next what we should do logically. So next logically what you should do you have current I and you need to convert it into voltage correct. And the best IC or a component that you can use to do a current to voltage conversion is as you must have learnt during the duration of this course and you are you might learn during this course is to use an op-amp.

(Refer Slide Time: 05:30)



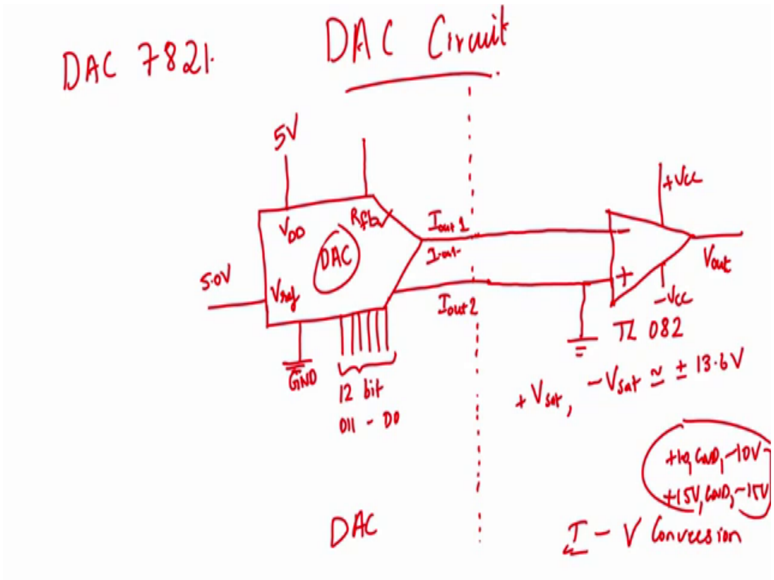
So, this much portion is your digital to analog conversion correct now we have the current to voltage conversion correct. So, what to do for to do that what do you need so you need to connect an first you put a op-amp.

So, in the board have this TL 082 op-amp so we will use that the op-amp will have output V out it will have supply rails plus V cc and minus V cc. So, on the board I release this op -amp should work at from plus 10 ground and minus 10 volt, but we have we are we will we will work it out with plus 15 ground and minus 15 volt and it will work if this voltage rails also. So, it is designed for sufficient tolerances, then what do we have then we have the non-inverting terminal and the inverting terminal. So, we will do the current to voltage conversion through the inverting configuration ok.

So, if it is inverting configuration what will be the non-inverting terminal the non-inverting terminal will be grounded like this ok. And then as we have discussed previously the; I out 2 should also be grounded as per the guidelines given the data sheet. So, the data sheet occasionally for every IC they will give certain guidelines we should follow it ok. Then the I out on is our current output right I out correct and we need to convert it into the voltage output V out. So, what you do and what is input of the op-amp for doing the current to voltage conversion it is this inverting terminal so just convert this I out 2 and here ok.

Now, next what it is yes correct so feedback has to so now, if you dies just leave it like this it will still do current to voltage conversion, but what is the problem there since there is no feedback given on this op-amp ok. Since, there is no feedback given for this op-amp it will work in what you called open loop configuration it will work in open loop configuration.

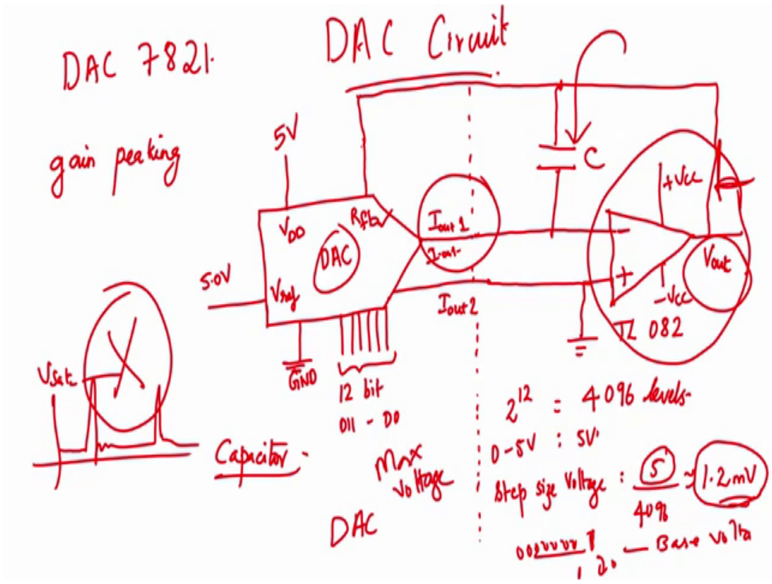
(Refer Slide Time: 07:55)



But in open loop configuration it works like a comparator, and when it works like a operator it will immediately go in to plus V sat V saturation or minus V saturation which is roughly around 3.6 plus or minus 3.6 volt which is roughly around plus or minus 3.6 volt for a V cc of 15 plus or minus 15 volt ok. So, we should have a negative feedback so that our gain is controllable and we will get measurable output values that change with the change in the bit sequence. Because if we if you do not do that right in the circuit whatever small input we give, because of the infinite gain of an open loop configuration of an op-amp ok.

We will always get saturation voltage only as the output that is why feedback is provided and these are basic concepts in op-amp which we will reiterate again and again so that it becomes very, very solid to you. And you can use his concepts to build intelligent systems; going further we will immediately going further we will see other applications also where we can build systems slides such as this ok. So, now R feedback is there correct so R feedback now has to go to the output like this correct.

(Refer Slide Time: 09:05)



Technically this is all wire is there for the circuit design to test it out, but then because of volt reference voltage fluctuations supply voltage fluctuations or output current fluctuations they you observe something in practical circuit design called gain peaking what it is called gain peaking. What happens is occasionally for a fluctuation in input voltages or output current here you we might get saturation output voltage as blips in the output let us say the output is supposed to be like this.

And sometimes because of some blips we will get like this and this will be V sat saturation voltage, but we do not want that this is we do not want this is not good circuit design.

So, usually what is the component that you used to smoothen out or smoothen out your signals. So, yes you guessed it correctly the component used to smoothen signals is the capacitor ok. So, what we do is we will connect a small capacitor like around point one Pico farad or in Pico farad or Nano farad range here. Across the feedback path and input path so that whatever peakings are there it gets absorbed or smoothed and out by the capacitor ok.

So, this is how with this capacitor we will get smooth output signals, but we play pay a price for this I will not get into details again, but if you do circuit analysis of the output voltage. Because of this capacitor you will find that the output gain gets reduced a bit and we might not get the full voltage fluctuations at the output. But none the less we will be able to see changes output voltage as and when bit sequences are changed which is digital to analog conversion correct.

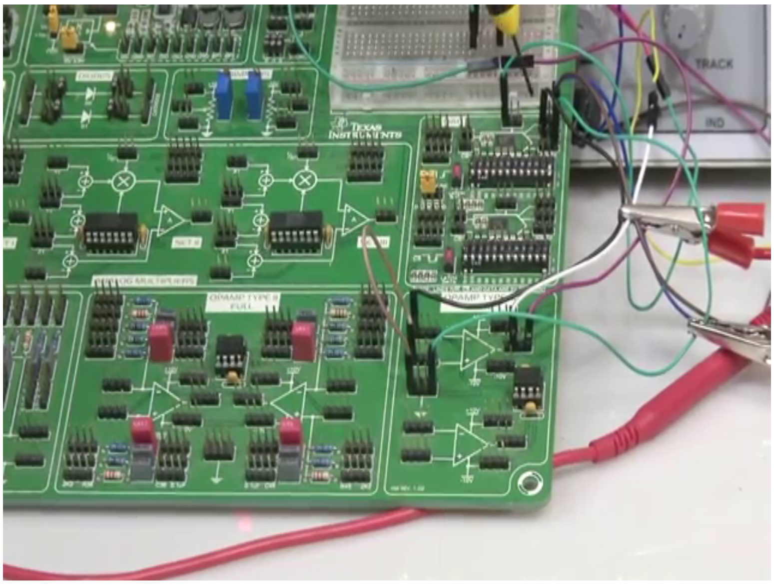
So, let us go back so let us suppose we have V reference voltage of let us say we have reference voltage of let us say 5 volt. And you all know that this is a 12 bit that that correct 12 bit that that means, it will have how many levels it will have 2 raise to 12 equal to how much 4096 levels correct. And your total voltage swing is what if say if say your via reference voltage is 0 to 5 volt your voltage swing will be 5 volt correct.

So, your step size voltage step size step size voltage for each change in bit sequence would be 5 by 4096 you can do mind calculation itself on that you did not use calculator for this will come to around 1.2 millivolt for each change in bit correct.

But then there is one more thing, because we are using an amplifying amplifier stage and it is a negative feedback amplifier. And we do not actually have a feedback resistor we have capacitor only in the path. So, the amplitude the maximum amplitude may get reduced when we actually practically implement it that that has to do with all frequency changes noise levels everything in the circuit. So, we will see what is the base level when we start off with the bit sequence bit sequence of say 0 0 0 0 0 0 1 first bit first bit turned high then we will turn this to 0 and turn this to 1.

So,. So, that 1 1 bit we are we making we will see what is a base voltage we get and what is the increment per bit. So, ideally we should get around 1.2 milli volt we will see how much we get, and we will also see what is the maximum voltage; we are seeing when we see the circuit clear. So, this is the circuit that we are going to see. Now this we will connect it up in the board and see how digital to analog conversion happens ok.

(Refer Slide Time: 13:11)



Now, let us see the board as we have explained in previous lectures this board has 2 DAC systems same IC 2 sets of circuits same circuits are provided on the board. So, we are using the top section you are using the top section and what are the main we have already seen the circuit design. So, we will just go through what are the main things should look at here and then see the connection and see what is the output we are getting.

So, this is the tri states switch that is provided for giving the bit sequence so from D level to D 0 12 it tri states switch ok. So, here we can have 0 1 or a tri state level to give 1 0 whatever bit sequence we need ok. And then we have the supply lines and there is something called digital logic supply here which is the logic line supply voltages. So, this we can give through either the DC-DC voltage or through the low dropout voltage. So, this is DC-DC and you can have a switch selection so we have kept the DC-DC level ok.

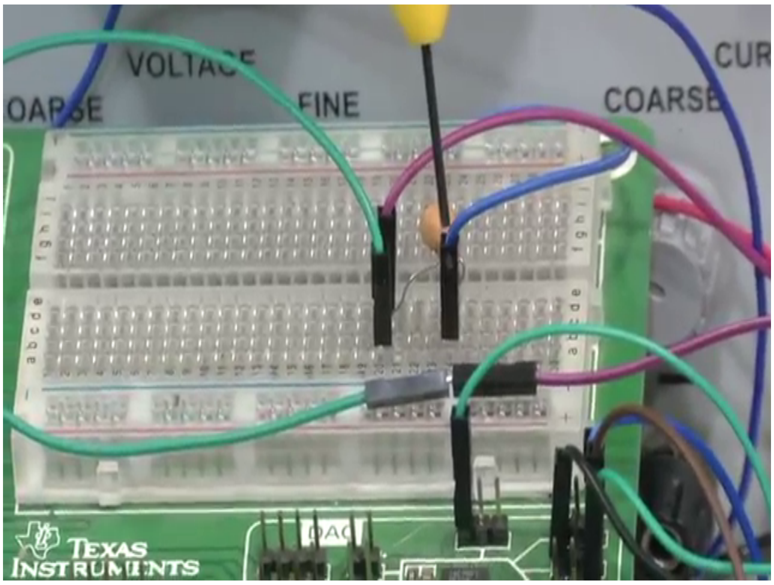
And then so same the main three connections that so you have you might have there are five main connections here after that one is actually six main connections we have might have we have we have gone through the chip select line right. So, this is the chip select line so it has to be 0 for this chip to be selected. So, it is by default grounded routed to 0 and if you want to bypass it you can bypass it also true this burg and we have the read or write burg that is this same connections are there in the top section also. Because this is more visible to you we are explaining with this plus the connections are also not made on this blocks block so it is more easy for you to visualize ok.

And then what is there is the reference voltage what is the V reference voltage for your digital to analog conversion. So, that is given through this burg we will be giving five volt V reference voltage from the same DC-DC converter which we are using to give supply to the digital logic; supply here same supply will be given to the reference voltage which is here if you can see ok. Then the other three main lines are the output and the feedback resources. So, this is I out 2 this line is I out 2, this line is I, out 1 and this line is the R feedback what is the importance of R feedback, what is importance of I out 1 what is importance of I out 2 everything we have a covered just now when we did the circuit design ok.

Now, let us see how the circuits are connected by zooming out good so the I out as we have to connect the output and the feedback to a op-amp section here in an inverting configuration. So, the I out 2 is connected to the ground here and also the non-inverting terminal here plus is also connected to ground here. And I out 1 is connected to the inverting terminal input here you can see it. And then the feedback path that is here is connected to the output section here as per our circuit design and we have also connected.

So, as per the circuit design here it is there they may have connected and as per our circuit design we have also connected a capacitor between the feedback line which is there in the. So, if we have to add an extra component we have to use the bread board that is provided we have seen that. So, you we have used a capacitor above here if you see so we have added this capacitor this yellow color component which is the capacitor.

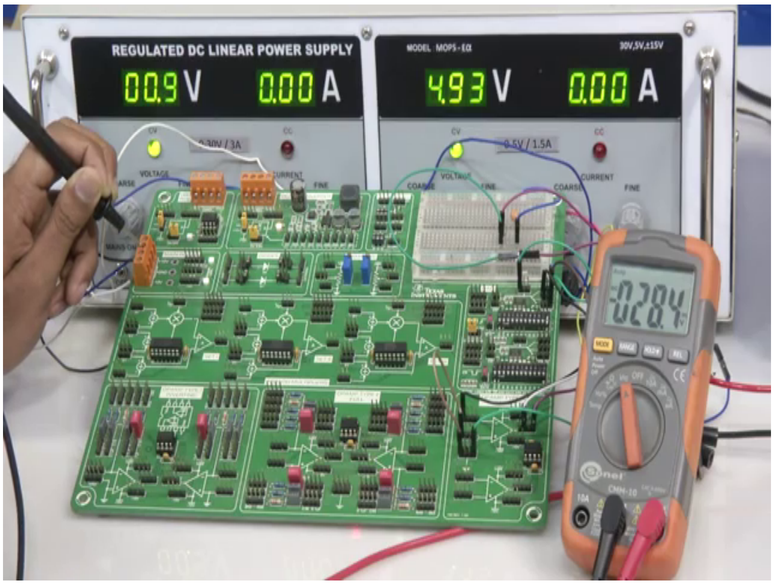
(Refer Slide Time: 16:46)



This capacitor we have connected between the feedback line and the inverting input terminal as per the circuit design for avoiding gain peaking ok. Now, we are all set to see the connections now let us focus on the tri state logic for the bit sequence ok, now you can see it. So, if you see now we what we will do is we have given supply everything is then ready.

As I have told you that because of the circuit limitations, and because of the fact that we have added a capacitor for gain peak adjustments we might not get the full output swing. But still we will be able to see; what is the change in the output voltage when we change the bit sequence which is what digital to analog conversion is. So now, if you see the bit sequence the bottom position is 0 and the top position is 1 ok. So, now, we have given 0 0 0 0 0 0 with last bit as one let us see what is the output voltage. So, we have a multimeter; so we have a multimeter connected to the output line and ground to see the output voltage.

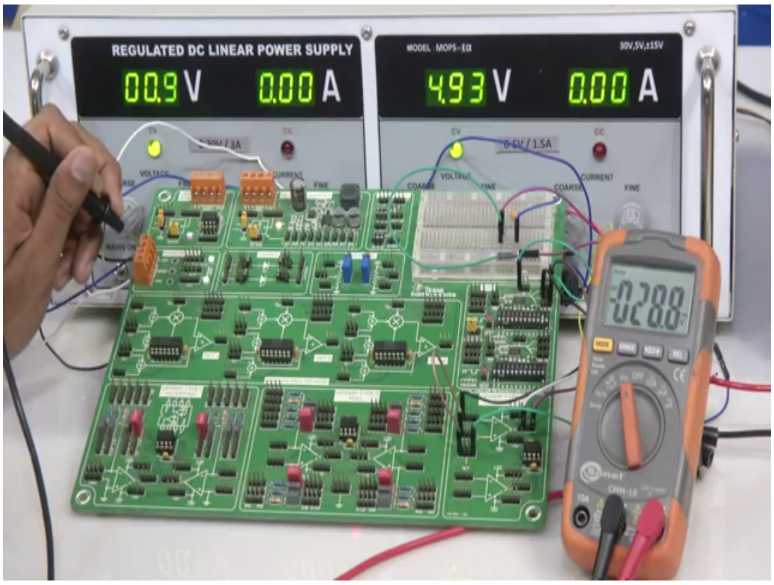
(Refer Slide Time: 18:03)



Because we have use the inverting configuration we will get negative voltage as a output. Let us now focus on the multimeter: yes, now we can you can clearly see it correct. So, what we are saying so our bit sequence is 0 0 0 0 0 0 last bit 1 so we have got 28.5 millivolt correct around 28.5 millivolt.

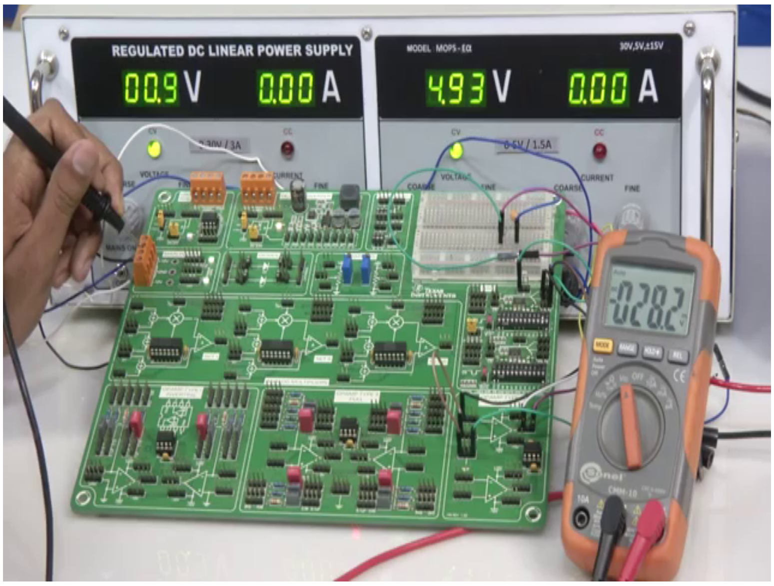
Now, as per our calculation we did that 5 5 by 4096 roughly for every bit change we should get around 1.5 millivolt increase. So, let us see what we are getting now we will make the second bit one and make the first bit 0. So, that we are doing only 1 bit change so now, what we have done, so what we have done is now we have probing it again.

(Refer Slide Time: 19:22)



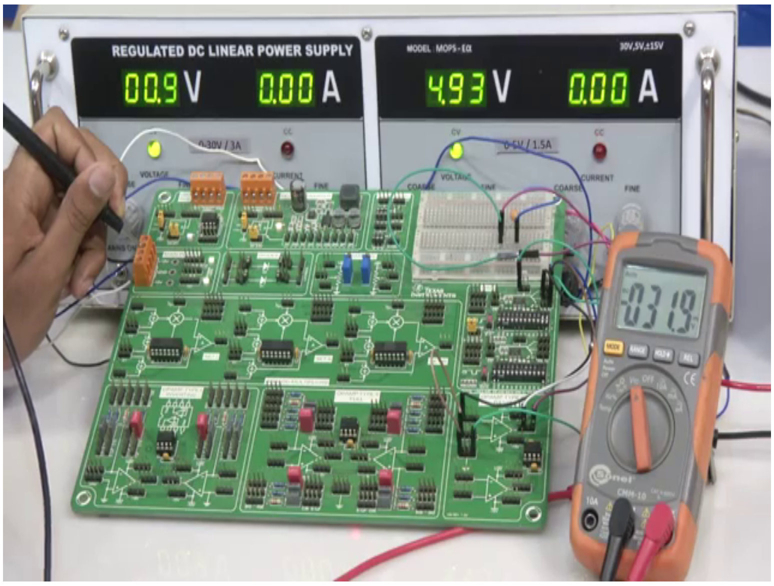
So, it was 26.4 before now we are getting 28.8 so it is around 2.4 voltage roughly we have got around 1.5.

(Refer Slide Time: 19:34)



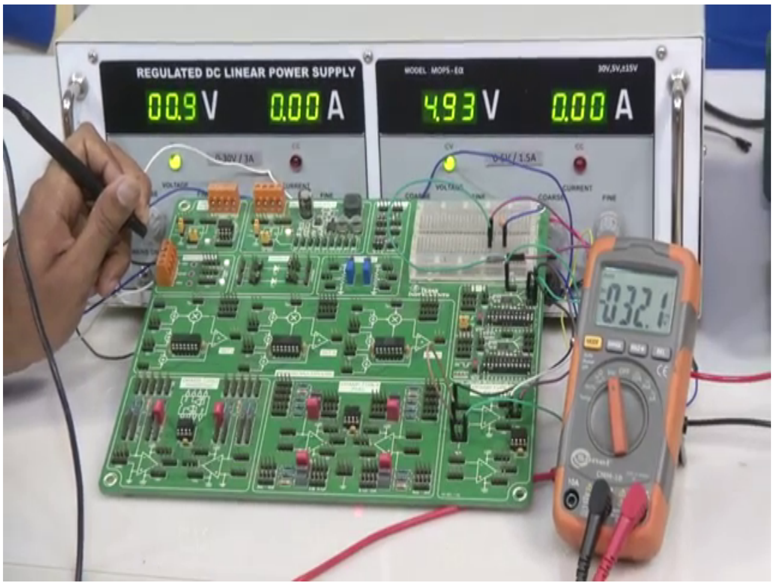
So, we are getting in that range the voltage changes you remember that this is in milli volt range, so noise components also will be there, but we are seeing a change ok. So, now let us so now, what we have done we have done the D 1 bit as high and brought the D 0 bit as 0. Now let us I have keeping the multimeter as it is connected with my this hand let me just change the first 0 bit also now 2 bits will go high. So, accordingly you see a change in voltage it has become 31.9.

(Refer Slide Time: 20:02)



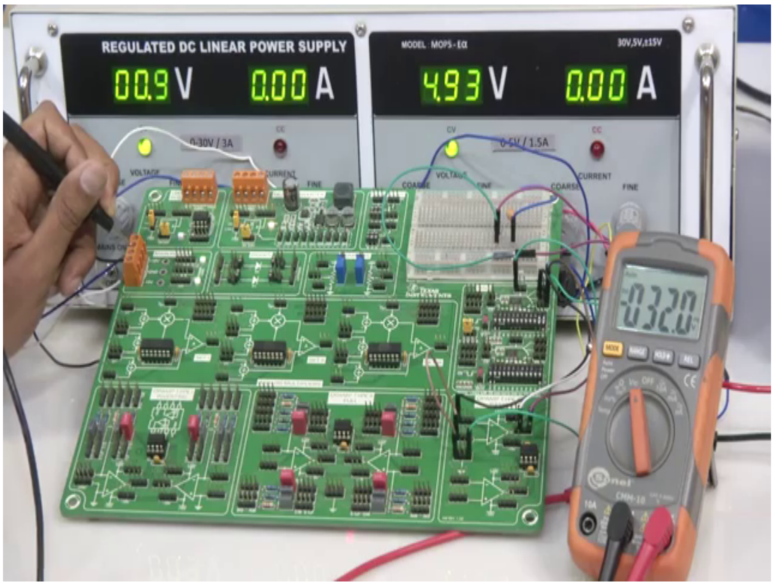
So, is roughly 32 millivolt so what was the previous voltage it was 26.4 now we added 2 bit change.

(Refer Slide Time: 20:09)



So, we got a change of around 3 point 26.4 to 32 correct so we got around 5 5.86 around 6 millivolt volt change. Now, let us increase one more bit now we are keeping the other 2 bits high. So we are going in not in changing 1 bit at a time we are changing actually double because we are not going removing the other 2 bits to 0; we are keeping them as one and keep on increasing the increasing bits to high.

(Refer Slide Time: 20:38)

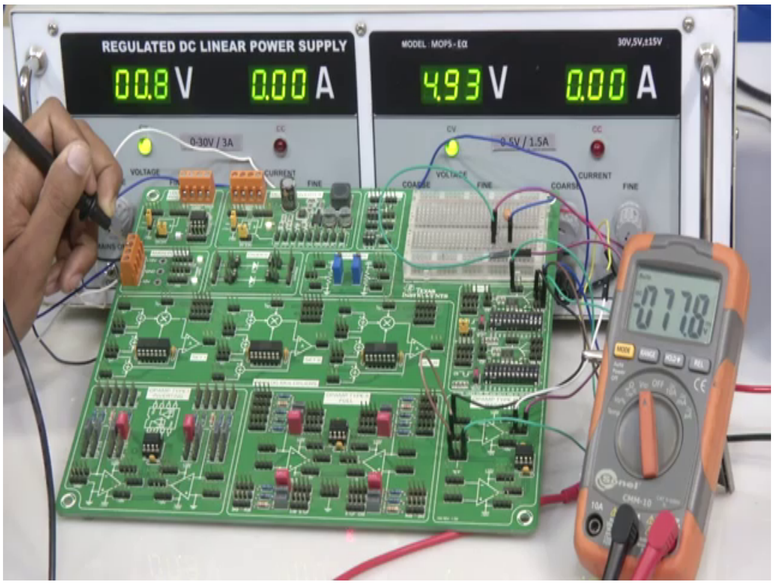


That is D 0 D 1 are one now instead of keeping D 0 D 1 as 0 and then changing D 2 D 1 we will do D 0 high D 1 high D 2 high. So, instead of getting 1.5 to 2 millivolt increase per bit change we will get double of that around 4.5 to 5 here we are getting around 5.5 millivolt, but roughly in that range we will get.

So, now D 0 is high D 1 is high and we are getting around 32 millivolt change; now I will make D 2 as high. To ensure that our circuit design and connections are proper the best way is to make sure that we are able to predict what voltage we will get when we make a change in the circuit that shows the robustness of our design the calculated values might not match.

But the curve the relationship or the linearity if it all their relationship is linear should be maintained that is what we should look at. So now, we saw that I by adding retaining the other 2 bits as high by adding one more bit as high we will get around 5 to 6 millivolt increase correct. So, this should go to around 37 to 38 millivolt when I change D 2 to high so let us see that so we will change D 2 to high ok. So, now we have changed under bit now which is the D 2 bit correct. So, we are getting 77.7 roughly 77 millivolt why are we getting like this.

(Refer Slide Time: 22:03)



Yes you have to make sure you have to understand that each bit has its own weight so 0 bit is 2 raise to 0 first bit is 2 raise to 1 and the D 2 bit is 2 raise to 2 that is 4. So, your relationship is not actually linear but you are having a not exponential the A raise to 2 or the 2 raise to A curve if you actually look at the mathematics of it, because of that we are seeing this change. So, we jumped from around 37 because now it is what earlier what it was it was 2 raise to 0 2 raise to 1. Now it is 2 raise to 2 it is almost doubling from 2 to 4 the weight of that bit because of that we were having 37 millivolt we came to roughly around 78 millivolt range.

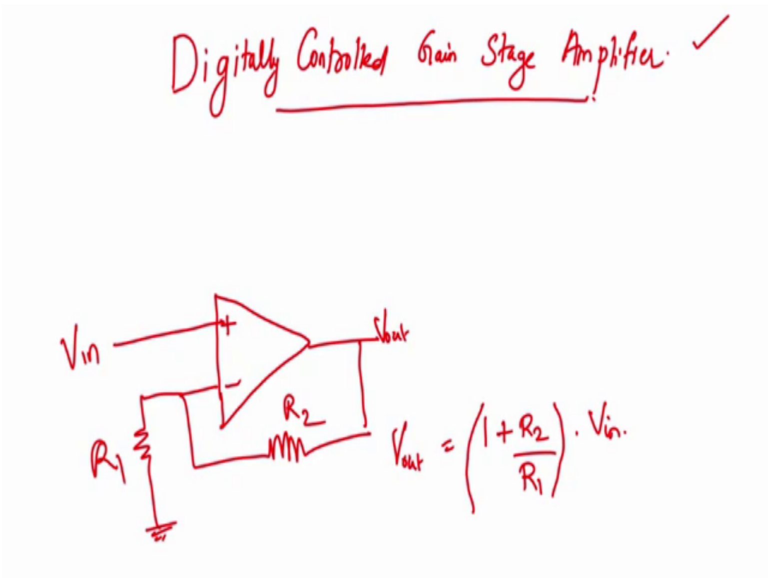
Now, let us change the next bit and see what we are getting see this. So, we got 136 137 its doubling because we are changing each we are adding one weight per bit now from 2 to 2 bit we have gone to 2 raise to 3 bit so we are adding one more two. So, it has become 137 millivolt, but you can very clearly see the digital to analog conversion happening from low voltage of 31 millivolt 26 millivolt with 1 bit high we have reach to 137 millivolt, to make sure that this is working properly let us go back to our ground state.

So, I will make this D 3 D 2 D 1 bit 0 and then retain D 0 bit as high, so we should go back to something around 26 millivolt yes we have gone back to 26.2 millivolt that means, that work the circuit is working very robustly.

Now what I will do is we will make the last bit D 12 bit high which has very high weightage. So, because of that the voltage will go to reasonably very high value ok. So, I have changed the bit sequence so we are getting 236 millivolt 244 if I change one more bit let us change one more bit now 249, so this is how the digital to analog conversion circuit works.

So, I hope you understood how the voltages are changing when we change the bit sequences we can even use these digital to analog conversion circuit and we have understood why current to voltage conversion is required. So, that we can see the voltage itself and make use of the voltage for other further applications. So, this completes the digital to analog conversion experimental part. And we will also see if you can use this module for other interesting applications.

(Refer Slide Time: 25:04)



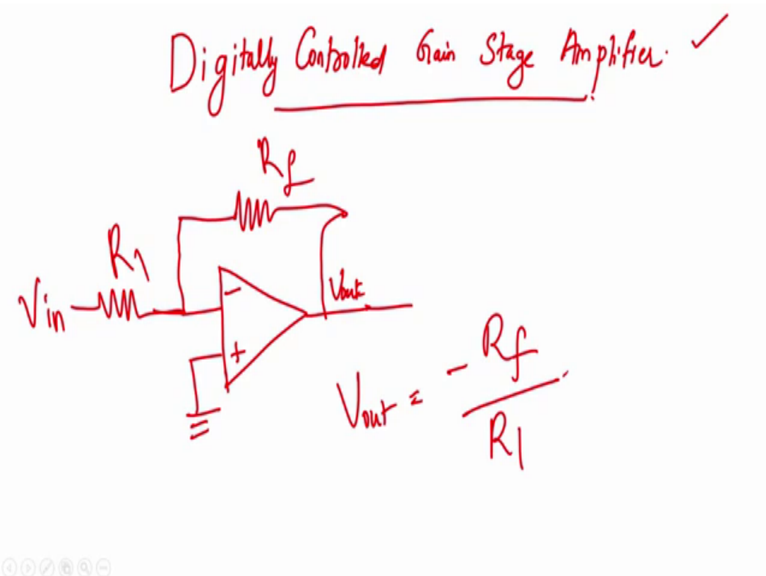
We will be seeing another interesting application of analog circuit design; where we will see how the analog circuit design can be done at the interface of digital and analog domains. Which is quite interesting from a mixed signal design point of view this is not exactly mixed signal design that is an entirely other bits in itself. But we you can get a few flavors of mixed signal design where your; so or where your PCB will handle both analog and digital signals that is the essence of mixed signal design.

So, today what we will be seeing is digitally controlled gain stage amplifier we want get into much theory about it, but like we have seen in our DAC module. We will see how we can intuitively design digitally controlled gain stage amplifiers, intuitive design is what we want you to develop in the course of during the duration of this course. Because this is a more practical oriented course at the end of if we expect that you are able to design few basic system on your own from the top of your mind with that actually looking up the internet for the circuits which is what many of us do.

So, let us see so what we are trying to do is digitally controlled gain stage amplifier let me give you the intuitive way of designing the circuit. So, what is the amplifier ok, let us say you all have covered you must know you must all have become now experts in non-inverting amplifier configurations correct. So, let us see how non-inverting amplifiers are designed non-inverting amplifier how it will be we will have an op-amp.

So, you have plus minus output to give the input directly to this V in and you will have a feedback negative feedback resistor R 2. And you have another resistor connected to ground which is R 1 and your output will be V out is equal to 1 plus R 2 by R 1 into V in correct. So, these things you would have you have you already know these are the basics of an amplifier inverting and the non-inverting amplifier. So, this is a non-inverting amplifier same way the inverting amplifier how does it look like quickly; let us go through it, how does inverting amplifier look like looks the inverting amplifier looks like this.

(Refer Slide Time: 27:33)



So, you have the op-amp again you have the output you have the inverting terminal you have the non-inverting terminal the inverting terminal is grounded you should always make sure that for amplifiers you should have negative feedback ok. And then we have V in here coming here, and you have another resistor we have Rf feedback resistor you have R 1 and your output is what V out is equal to minus Rf by R 1. So, this is your inverting amplifier configuration correct.

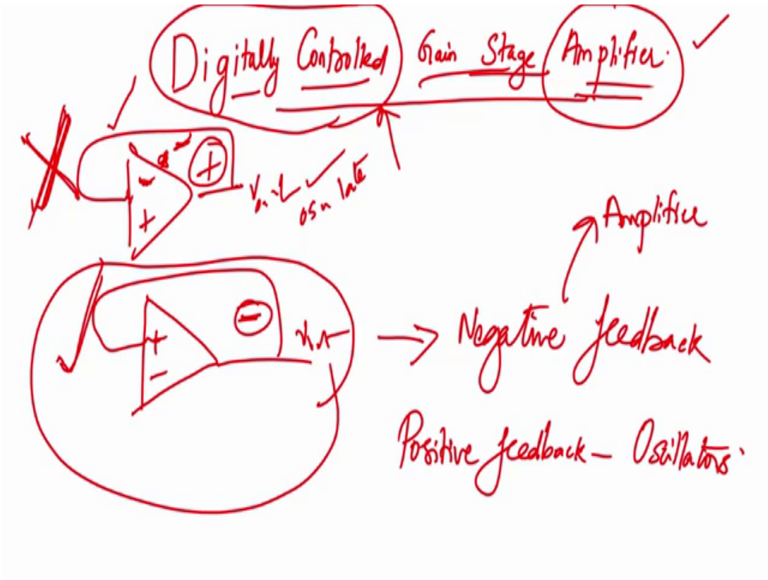
Now, what we are trying to do here today is not is not exactly related to any of this will it be possible for us to on the fly using digital logic change the gain of an amplifier. So, that is what is meant by digitally controlled gain stage amplifier that is what is meant by digitally controlled gain stage amplifier.

So, how can we do that so that we will do by integrating a DAC to the amplifier stage? So, already we have seen an experiment where we have given a bit sequence to the DAC correct we have given a bit sequence to the DAC and it has gone it will give a current output correct. And the current output is converted to a voltage correct and the voltage we will visualize as the analog version of the digital input signal.

So, can this voltage be used correct can this voltage be used to give what is it a differential or a controlled gain to an amplifier remember that this DAC. So, remember the DAC output when we saw it was a negative voltage correct and we have covered now that what is it we have covered now that when we are deciding amplifiers the feedback should be negative. So, for the feedback to be negative either your output should be connected to your inverting terminal correct or you can convert you can connect it to your non-inverting terminal.

But your feedback voltage itself can be negative in two ways you can have negative feedback correct you can either convert a you can either connect a positive voltage.

(Refer Slide Time: 30:10)



Fraction of the positive voltage of your output to your negative terminal correct this is negative terminal correct. Or how you can do negative feedback you can convert a portion a negative portion of your output voltage to your positive reference that is also negative feedback correct is the two ways you can do it.

I am trying to tell you how intuitive design is done that is why we are going like building blocks here correct. So, which scheme do you choose any way we need to control the gain of our amplifier correct. And we are telling that we are going to control it digitally we are using digital control we are using digital control for the gain of your amplifier correct.

So, and we also know that our DAC output as per our previous experiments is a negative voltage. So, output is negative we will use a fraction of that output voltage to give feedback. So, if you use this scheme then here also it will be negative here also it will go to the negative terminal. So, you will get overall positive feedback and the output will saturate or oscillate ok.

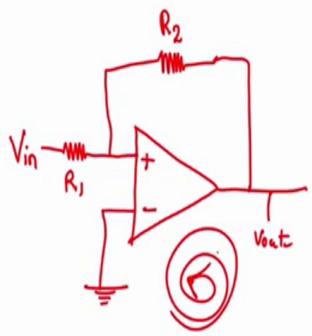
So, instead of that this is not the scheme that we should choose is it understood hope it is clear to you. So, we have to use this scheme correct we have to use this scheme for giving negative feedback. And negative feedback is what is required for amplifiers and negative feedback is required for amplifiers and positive feedback is used for yes correct oscillators correct.

So, one learning is done so what we are doing we are taking a problem what is our problem our problem is to design a circuit to do digitally controlled gain stage amplification our problem is to do digitally controlled gain stage amplification. So, we are breaking down the problem and seeing how digitally controlled can be incorporated into gain stage amplification for that we know the amplifier design which we have covered which is very simple. So, amplifier design is very sure very clear to us ok.

Now, amplifier design is very clear to us and we know that in amplifier you should have negative feedback, but we have the constraint that in our digital control our DAC output is negative. So, how can we implement negative feedback using an output which is already negative what we have to do we have to use this scheme; is it clear to you this is how we do intuitively design. So, it is very clear things are coming automatically to you ok. So let us get into the get our hands dirty and get into the circuit design correct.

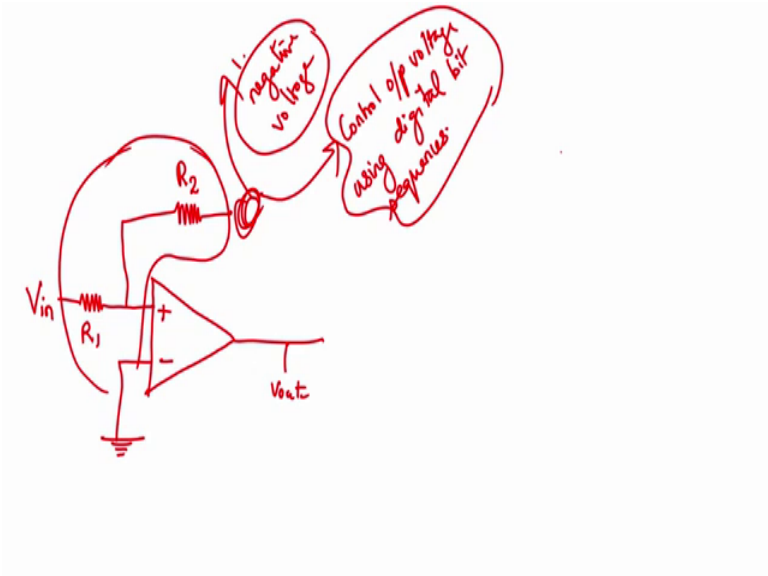
So now, we know that our feedback should go to the negative terminal correct positive terminal because our output voltage is itself is negative so let us make the circuit.

(Refer Slide Time: 33:14)



So, our scheme will reverse, so this will be plus and this will be minus and this will be our output voltage V out this much we know correct, because scheme is like that we will ground this terminal clear. Now, we will give input here V in through a resistor R 1 so we have another resistor here R 2 clear. Now if we connect R 2 here like this will become positive feedback because your output is already positive, because it is a non-inverting configuration correct and you are giving a positive feedback. So, this will go into saturation and even oscillate correct so then this is not what we should do.

(Refer Slide Time: 34:15)

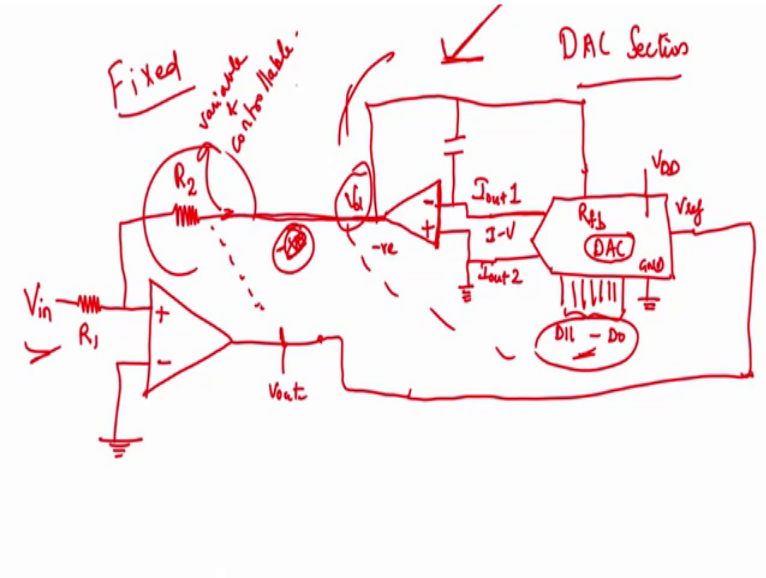


Here is where so here there should be something that can do two things what all one is give a negative output negative voltage negative voltage contribution another is controlled output voltage using digital bit sequences correct two things you should have negative voltage. So, that we will have negative feedback so the amplifier operation can work properly and we should have controlled output voltage that will change with bit sequences.

So, that we can do a digital controlled of the gain stage which is this is the gain stage this is the stage. So, the gain stage of the amplifier can be digitally controlled using a DAC this is where the learning's you would take from your previous modules ok. We can use to make beautiful circuits this these circuits if you look at it from a practical implementation point of view these are beautiful I will come to the practical implementation of it how important this is; this circuit is that is why we wanted to cover this part with you now this part is clear.

Now, you are your all masters of this part now we have to make a DAC right. So, let us that make that DAC separately here so this will be the fixed amplifier section and this is the DAC section for us to digitally control our amplifier correct.

(Refer Slide Time: 35:44)



So, let us not worry right now about connecting this two and getting our final implementation which is the digitally controlled gain stage amplifier. Let us see our DAC section we have do DAC section. Now I think you are very well aware and you are you are masters of that part. So, let us just do the formality of designing it so let us a DAC. So, we will have a V ref let us keep it there you have a VDD you have a ground which is grounded here you have a feedback resistor R fb.

So, this is your DAC you have I out 1 you have I out 2 correct as per our previous design I out 2 is should be grounded correct and for us to do current to voltage conversion this we have to connect to another amplifier all this is I think very clear to you now. So, the amplifier will again we have a negative feedback. So, in the positive terminal will be grounded like this along with I out 2 correct and I out 1 will go to the negative terminal like this clear right.

So, what will happen this is the output of the amplifier which will be a negative voltage correct. Now we know that the feedback has to be connected to the output this also is very clear to you we have gone through it in detail. So, the feedback is connected now what is missing what is missing from our previous modules yes we need to do the control for gain peaking.

So, we will add capacitor here correct cool now what we have done. So, this that portion is ready it is ready here cool that portion is ready now we have the fractional. So, we what else is missing here missed a very important thing here correct we miss the digital input know, so digital input will be there D 11 to D 0 which will control the output that you finally, get here correct.

So, what is the controlled? So you are able to control the voltage here Vo 1 using the digital bit sequence here correct. Now how do you connect these two? Now we understood we have learned that this feedback path for it to become variable and controllable what is it variable and controllable. For it to become variable uncontrollable there should be some negative voltage that we can controlled that should add on to this voltage correct, so it is obvious correct. So, that we should connect these two correct, so this voltage that is coming from here this path gets configured by this bit sequence and it gets added on to the feedback path.

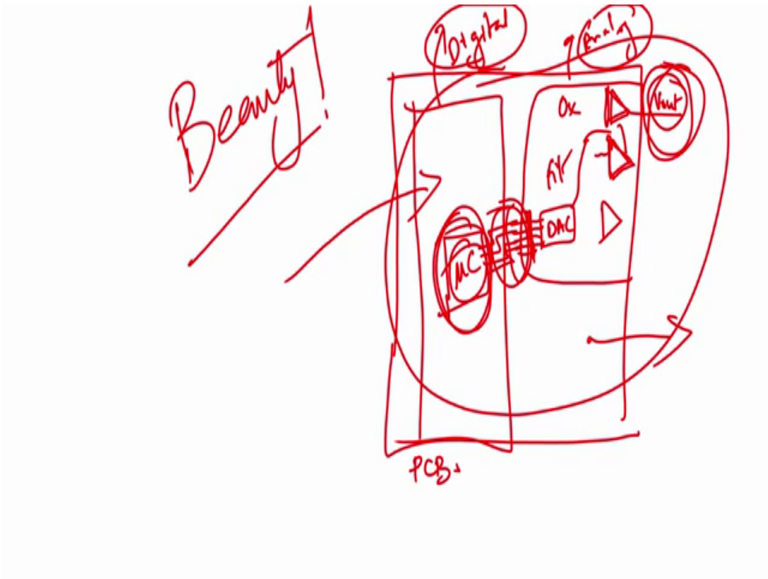
Now, still the feedback path is not completed correct the V out still dangling here the V out should; finally, connect here know ideally it would have it was connecting here, but then we have added a changing negative voltage controllable voltage component there so it is simple now you understood right. So, this has to go back as your reference voltage so that we complete the circuit. So, vi output we will go as your reference voltage so the reference voltage will control the levels of your output voltage here which will give a negative voltage and that will add on to the feedback path here and we have our input voltage. And we can see how we can control the gain with this mechanisms see how beautiful the circuit is its very beautiful right.

We have used two concepts which we have learnt what are the two concept which we have learnt one is digital to analog conversion and in that process of learning that we have learnt current to voltage conversion ok. And we have used so we know that with a bit sequence I applied that the input of the digital to analog converter we can have a negative voltage that is concordant corresponding to the input bit sequence correct.

And then we also studied about amplifiers what is amplification what is feedback what is negative feedback what is positive feedback what is non-inverting amplifier what is inverting amplifier these two strong concepts which we have learnt we have integrated to make something beautiful. What is a beauty here you will be able to control the gain of your amplifier by using the bit sequence.

Now, you might think what is so special about it I have to still change the bit sequences right I have to still change the bit sequence what is. So, digitally controllable in that yes and that is where you might be missing the point the beauty I will show you now.

(Refer Slide Time: 40:51)



So, let suppose we have a PCB and you have an analog analogue section in the PCB and you have a digital section clear. And your digital section is controlled by say a microcontroller mu C you have with the analog domain which have lot of amplifiers. Let us say and other filtering filters and all source of oscillators filters everything oscillators filters all these are analog domain this is your analog domain this is your digital domain of the PCB ok.

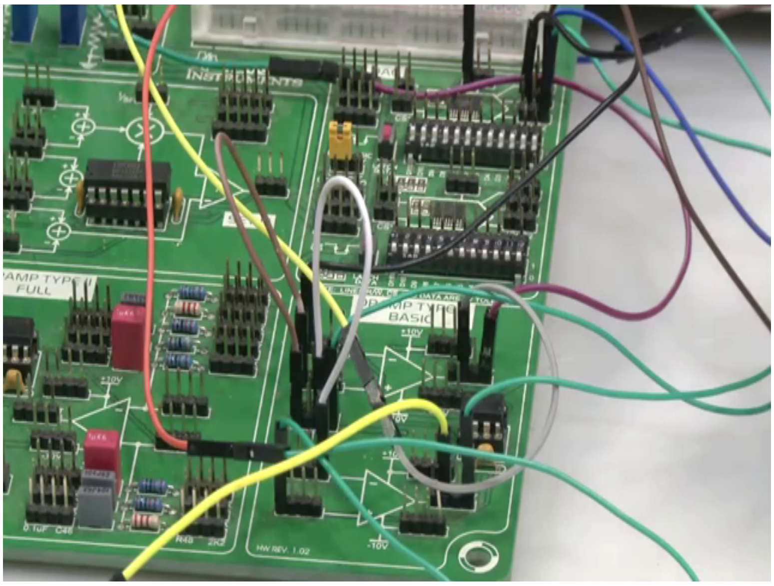
Now, you if you do hardcoded design your amplifications will be fixed so in during the time of bringing up of your PCB this is a kind of became your mixed signal PCB. During the time duration of peaking of a PCB you will be faced with either to desoldering of the resistance that you have used for an amplification finding your new resistors and then placing them back soldering them back to change your amplification or you can use this beautiful circuit to do control the gain digitally.

But how what will happened this amplifier as we have seen we will get connected to a DAC module correct and the DAC module what it will you the DAC module will have a bit sequence correct. And we know that by changing this bit sequence you will be able to change the amplitude of this output the amplification. And there comes a beauty you are connected the analog world correct with the digital world because your microcontroller will be able to talk to this bit lines.

And through your software which is loader on the microcontroller you will be able to change the bit sequence and thereby change the output voltage without touching any component on this PCB. Even after you deliver this as a product support and your customer faces some tuning issues some calibration issues because of the amplifiers output. You can always give a software upgrade to your board updating the firmware on your microcontroller which will change the bit sequences and you will give the output there is no soldering desoldering involved this is the beauty of such a design and we wanted you to appreciate this beauty ok.

So, this is how we can merge digital and analog domains and this is how analog circuit and digital design goes hand in hand ok. So now, I guess you are very well aware of the importance of the circuit how you we have done this design intuitively step by step, understanding each and every module in a very practical way we have not got into the mathematical formulation or anything. We have just taken blogs connected them together and now comes the fun part we will see the board and see if it is working.

(Refer Slide Time: 43:35)



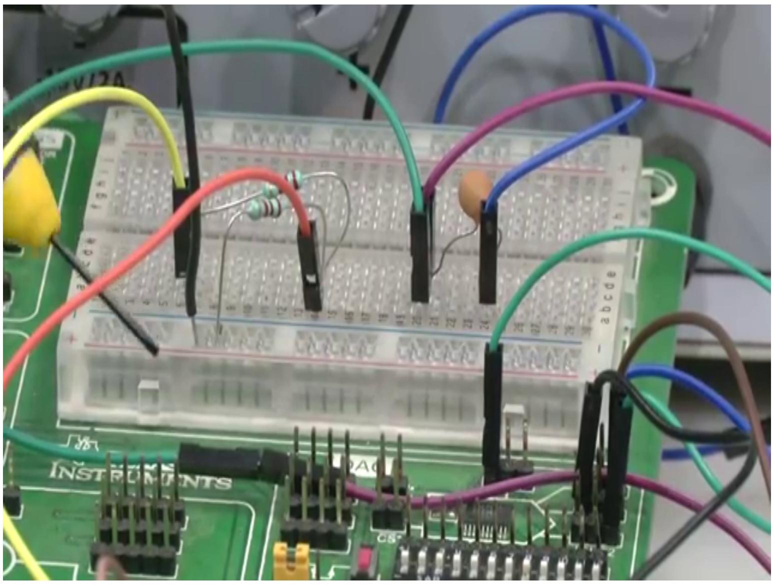
So, here we have the board where we have implemented what we just saw a circuit. So, what did we just see so we had that their DAC and we are trying to integrate now op-amp based amplifier with a digital to analog converter. So, that we will be able to controlled its gain digitally so that is what digitally controlled variable gain amplifier that is what we are trying to see.

So, here as we have seen before this is the DAC setup that is the digital to analog converter setup and we have the I out 1 I out 2 R feedback everything connected ok. So, in this implementation as this seen by the circuit that we just designed we have two op-amps to be used so these two op-amp. So, here you can see this op-amp section so we have one op-amp here and other op-amp here. So, one op-amp as we have seen is used to convert the current output of the DAC to voltage and that gets fed back into the feedback network correct and then is used up by the other op-amp whose output goes back as the V ref for the DAC correct.

So, these connections have been made here hope it is kind of a lot of connections are there because we are trying to use the jumpers on the board and connector, but the basic idea is basic idea remains the same. So, the DAC which is this one the DAC is connected and its bit sequences are here ok. And then the output of it I out 1 I out 2 goes to ground as well as the positive terminal of the op-amp goes to ground ok.

And the I out 1 goes to the negative terminal of one op-amp and R feedback goes to the output of that op-amp here and then both of them are connected to a capacitor here above on this breadboard if it can slightly go up, but you can see you are you had seen it in the DAC setup also. So, there is a breadboard here this white color section, so there we have kept a capacitor this white section. Then from the output from the output of that op-amp we have a resistor connected. So, we have a two resistor network R 1 R 2 we right now we have kept both same resistors.

(Refer Slide Time: 46:06)

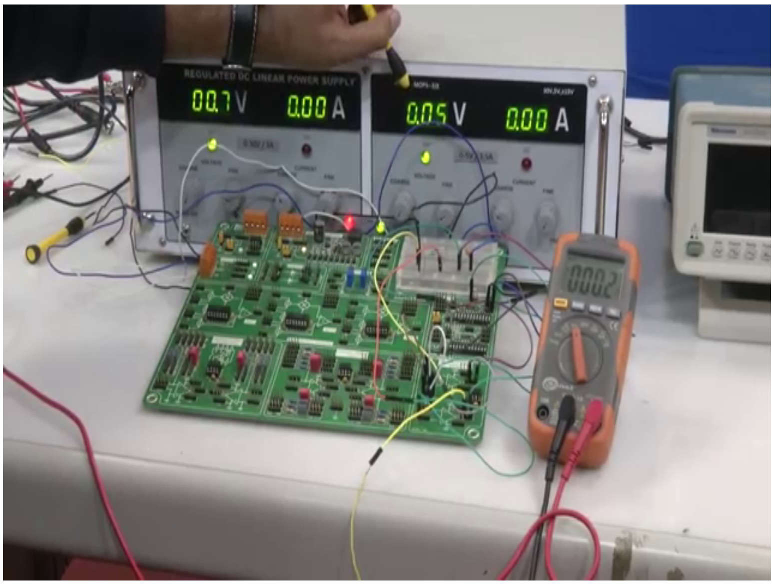


So, here we have connected the two resistors as we have seen so we have seen right. The amplifier in which the input was connected to the positive terminal of the op-amp through a resistor and the feedback path had a resistor on it that is connected to the DAC at digital to analog converter system.

So, these two are the same resistors for simplicity purposes we have kept the same resistor values here then that output. So, this goes to the second op-amp here below. So, let us see that yes, so it goes a second op-amp here below from here the output of this op-amp goes back as the reference voltage for the DAC. So, this green wire which I have held up you can see so this is the port for the V voltage reference and it gets connected to the output of the op-amp so this way this circuit is completed ok.

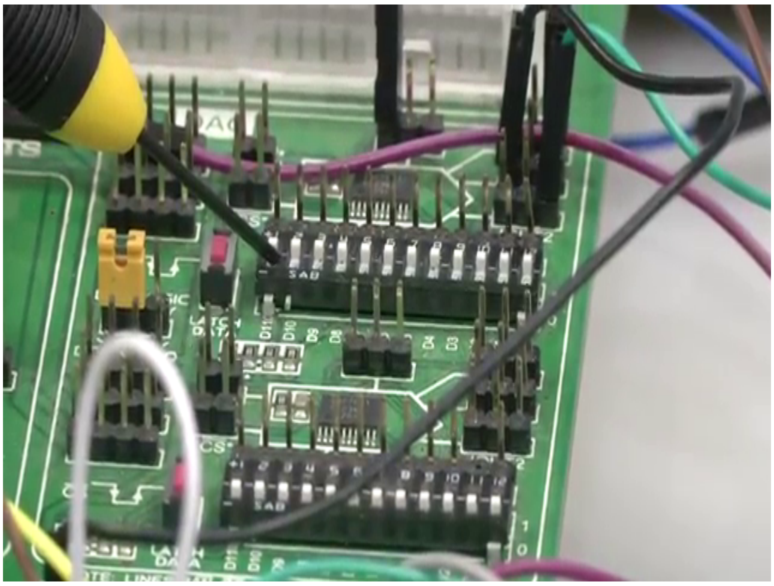
Now, we can see the output; so the output is the output of this for second op-amp which also goes as voltage reference to the DAC system. So, let us see how by changing the bit sequence we are able to see the change in the output voltage so if you see the power supply.

(Refer Slide Time: 47:29)



The input voltage is applied from this power supply there plus 15 minus 15 supply for the op-amps is given from this power supply the central power supply. So, we are applying an input of 0.05 volt or 50 milivolt and that that signal is applied to this; and through the resistor here. So, that signal is applied through the resistor here then now we will see the output by looking at the output of the op-amp.

(Refer Slide Time: 48:06)



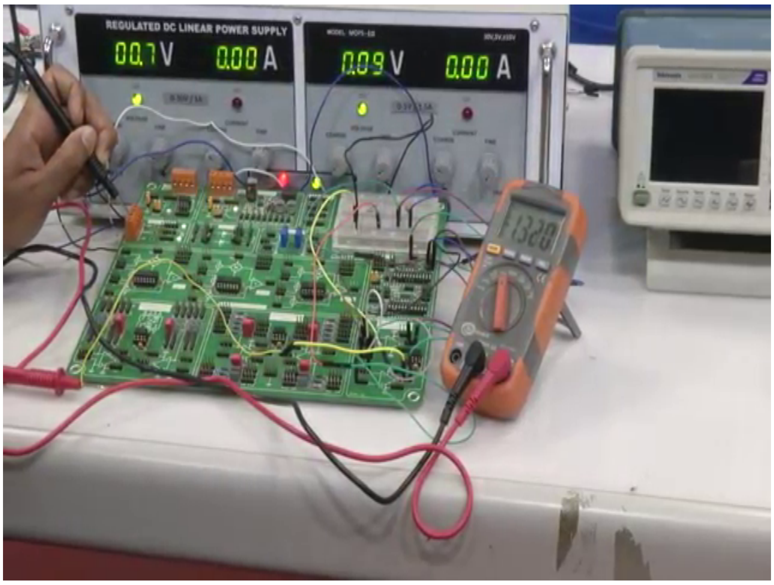
Now let us just focus once at the bit sequences yes, now we can see the bit sequences; if we can see now all the bits have been pushed up like this; now we will now only focused on the multimeter after this. Now I will be we you will not be seeing it, but I will be changing few bits in this and we will accordingly see in the multimeter how the voltage is changing. Now let us see what is the voltage when all the bits in the DAC are high so let us focus on the multimeter. So, I have not yet connected it so it is showing minus 309 millivolt for 50 volt input we got an output of minus 309 millivolt.

Now, let us just change the bit sequence, so I will change few bits to 0. So, you can see very clearly the voltage has gone up it has become 411 volt or 4 411 millivolt point 400 meters it was lower value before let us just go back to that lower value. So, that is 316 it is all it has almost gone up by 1.1 volt or 100 millivolt so gone up in the sense by absolute magnitude it has gone further negative.

So, let us just change another bit combination and see how the output is changing see as and as and when I am changing the bits the voltage is changing it has become 0.60 600.6 volt. So, let me change a more bits. So, it has become 0.745 I will check one more change one more bit it has become minus 0.966.

See through this way we are able to control the gain so the gain. So, we are seeing a swing from like 300 millivolt to only around 0.9 millivolt right that is because our input voltage is very less. Because input voltage is very less because the amplification will be there and you do not want the op-amp to go to saturation correct see I have changed a lot of bits now. So, it has gone to up to minus 2 volt for 50-50 millivolt inputs. Now, let us just do a small experiment let us just increase the input voltage to let us say 0.07 or 70 millivolt. So, you just focus on the multimeter I will just change the input voltage.

(Refer Slide Time: 51:03)



So now, it is point I have increased it to find 0.09 or 90 millivolt see the voltage now it is minus 1.333. So, let me change the bit sequences so it is coming down see so it is fluctuating in the sense it is just not fluctuating and changing as per our changes of the bit sequence. And one more thing you notice is that so when I go beyond like 100 millivolt, because the gain op-amp will be have two stages of op -amps here the inputs swing should be very minimal it its used for processing very small input voltages the moment I go to a high voltage.

So, till 290 millivolt it is whatever which gave 300 millivolt for 50 millivolt input my input is now 0.290 millivolt. So, accordingly our DC output has become 4.3 volt now it is 290 millivolt let me increase the input voltage see. So, it is 260 milli 260 millivolt now if I increase it at one point it suddenly goes to saturation it has gone to positive saturation, because now the amplitude the amplifications become too much that it has gone to positive saturation.

So, this way you we will be able to digitally controlled the amplifier let me go back to the low 0.06 0.05. So, its 0.8 80 millivolt and this is the output voltage let me change the bit sequences so we can change see the voltage changing ok.

So, this is how digitally controlled variable gain amplifier can be made; as I have told you need not actually go ahead and change this the bits like I am doing it this is only for educational purposes we are showing it like this to you. You can always have a microcontroller connected to your DAC input bus and changes the bits accordingly.

So, I hope this circuit was we have found the circuit interesting and in further modules we will see other circuits as well.

Thank you.