Circuits for Analog System Design

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Lecture No. # 02

Three Transistor Op-amp and Transistor Based Voltage Regulator

Good morning all of you. In the previous talk we had discussed about transistor amplifiers and then I also said that you know how the operational amplifier came from the transistor amplifier. And I said that I will disclose the name of the person who is responsible for the development of operational amplifier. So, now, I will just spend 5 minutes to recollect what we had done in the previous class.

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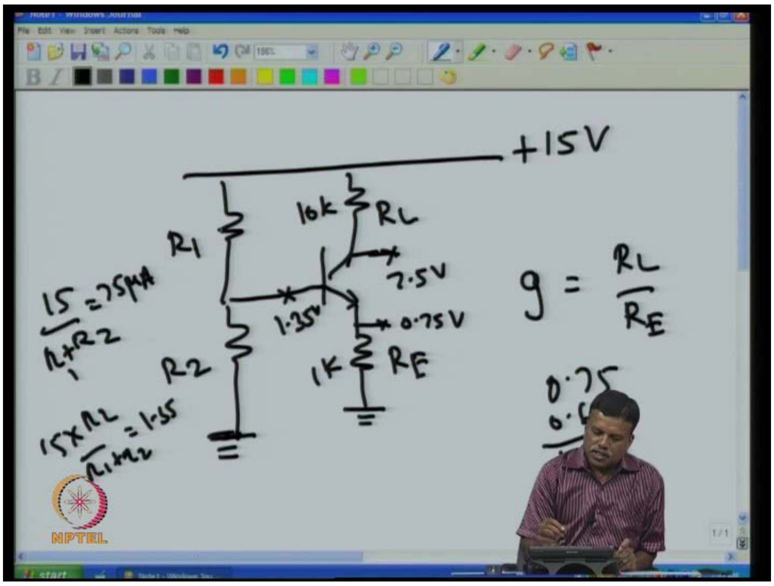

So, in the previous class that, we had talked about this transistor amplifier. That is, if, I have a transistor than if I want amplify A C signal then we had this kind of circuit. So, you had these resistors you know here it is grounded and then we connect the base to this. Then you know we are given a supply voltage here. Now, you know this is the load resistance and you know this is resistance which is connected to the emitter. The ratio between this and this for example, if I call this is R L and if this is R E. So, the gain of the circuit actually is given by R L by R E.

So, for example, I can have here 10 K and then I can have 1 K that will give me gain of 10. Now, these two resistors for example, R 1 and R 2 are biasing resistors. We set we are select these two resistors to get correct amplification. Normally, this is done by fixing this point. You know I take this. Fix this sincerely you know without any A C signal, I fix this at midpoint of 15 that is a midpoint of 15 is 7.5 volt.

So, you have to fix this at 7.5. So, if I have 10 K then 7.5 have to come here means then 0.75 milli ampere current have to go through this. Then same current almost goes through this that means the 0.75 milli ampere goes then this voltage will be 0.75 volt.

So, we have to adjust these two resistances such that this is sitting at 0.75 that will automatically call for 0.75 plus 0.6. That are 0.75 plus 0.6 that turns out to be 1.35 volts. So, this has to sit at 1.35 volt. So, I have to select this R 1 and R 2 such that this is sitting at 1.35. Normally, we have to find you know we can get various combinations to get from 15 volt. You know for example, you know in this case this is at 15 volt all that you need is at this point. I have to get 1.35 that will make this. Sit at 0.75 this point will sit at 7.5 that is the required starting point.

Now, I can get various combinations of R 1 and R 2 now the actual value depends upon what is the base current? If I neglect the base current I can take any value for R 1 R 2 to get 1.35, but, normally you know if I take this is 0.75 volt this voltage you know if I take this is 0.75 then the current through this is 0.75 milli ampere. Then if h f is 100 then the base current will be 750 micro amperes by 100 that will be 7.5 micro amperes. Then I can select the current of 75 micro amperes here with that I can select 1.35 here.

So, the 15 divided by you know a 15 volt divided by R 1 plus R 2 should give me 75 micro ampere current. So, then we know that 15 into R 2 by R 1 plus R 2 have to be 1.35. So, from this we can get R 1 and R 2. Then, once the this R 1 and R 2 is known then this transistor amplifier is ready for amplification. Now, I can apply A C voltage here I kept a decoupling capacitor.

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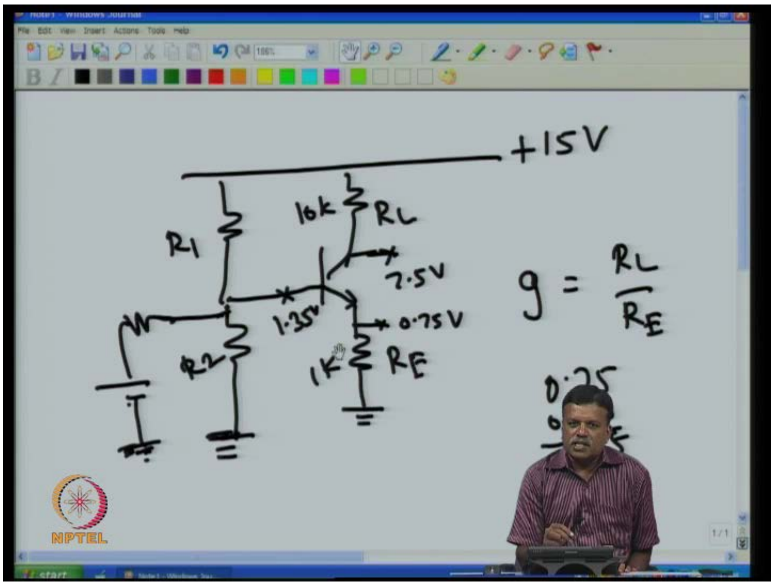

So, the D C voltage will not get short circuited through the c source. Now, I connect A C source.

Now, this voltage will be amplified and amplified voltage will appear here. This is the transistor amplifier which we have discussed in the previous class. Now, it is a very simple amplifier, but, nevertheless there are issues in this. Because, you know that is a good job for A C to amplify A C voltage, but, if I want amplify a D C voltage then we get in to problem. For example, if I want to amplify a D C voltage then I can apply I can do one way of doing this would be I can apply D C voltage here and then this voltage change will produce a D C voltage change here. That will produce a D C voltage change here like this we can use this to amplify the D C voltage.

But, one problem with this is that you know if I give this and get amplified voltage at this point. This change in voltage represents the change in voltage here that is, you know if this voltage changes, you know that this D C voltage also will change. Unfortunately, the change let us say I give at this not necessarily due to this alone. This voltage will change even when base emitter voltage of this changes. This base emitter voltage of this will change when temperature of this transistor changes. That means, when ambient temperature changes this voltage will change.

Similarly, if the supply voltage changes again this voltages will change because if for example, if this voltage increases then this voltage also will increase. If this increases then this voltage will increase and that will increase the current through this and that voltage will decrease. That means, voltage at this point can change due to this change in supply voltage as well as due to change in the temperature of this transistor. This was the biggest problem and then because of this, to amplify D C, we amplify the D C is difficult job.

And then there were various compensation techniques that were used and even difference amplifier was tried. But, then all these things are not very convenient use. As I said last time, it was the birth of the operational amplifier that actually made use of the electronic circuits particular, analog circuit very easy and then electronic started going only upwards.

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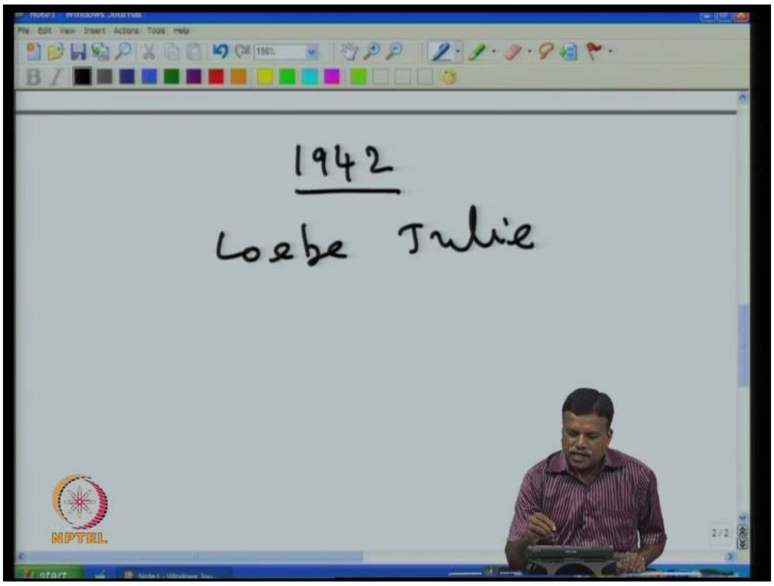

So, as I said, this all had started from in 1942, during the Second World War, that is during the Second World War. You know, they wanted to develop you know that is the British airlines was attacked by German aircrafts. So, they wanted to develop the anti-aircraft system. So, that you know when the aircraft is located in the radar automatically the gun would be fired and the aircrafts would be shot down.

That was the thing that they were looking and the job was actually given to the you know one Mr. Lorbe Julie. Who said that you can develop the so called the present operational amplifier in 30 days and then using that MIT, with the help of bell labs, supposed to develop the so called gun director.

So, actually what Lorbe Julie done was that he had developed the operational amplifier that can be too used to amplify A C as well as D C. And when you amplify a D C voltage the inherent problem that we have discussed so far that you know the output voltage can change due to temperature and change due to the supply voltage. That will not be there anymore and also one need not struggle hard to bias the transistor and then select the resistance and so on. Everything can be in built and one can use the amplifier as it is. So, that was the job that was given to Julie and he had done the remarkably that work.

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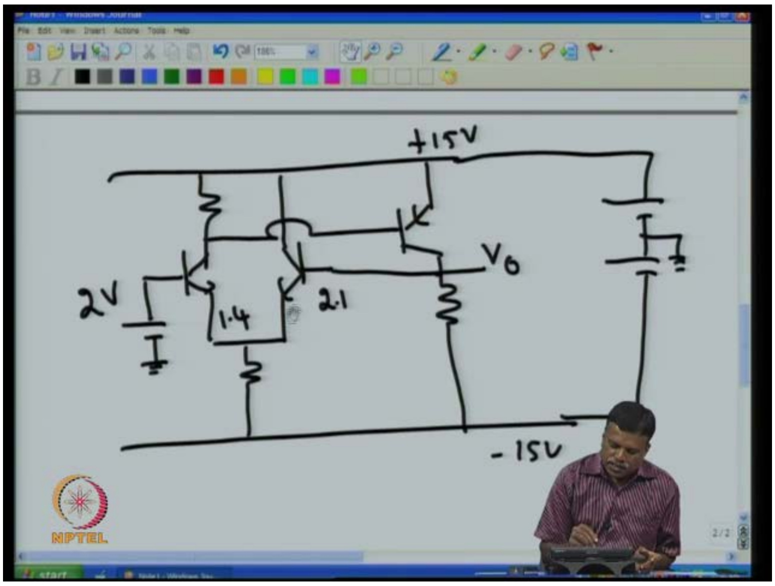

Now, if we look at that what is that he had done to solve that two problems, now, this amplifier was done with three vacuum tubes. And now, I will not be using the vacuum tube. I will be using the transistor equivalent of that so, the working of that. So, the circuit was quite simple. He had taken three transistors and they were connected like that. You know he had connected this and then this and this was basically connected to minus 15 volt, this was connected to plus 15 volt. In actual circuit it has plus 300 minus 300 this with vacuum tubes.

But, here we are showing with transistor then the third transistor was connected here and that was the operational amplifier that was used to develop that anti-aircraft. In fact, he had made 300 number of this and that was hardware to act as a computer to deal to direct the gun.

Now, you know what you can do is for example, here you know this is acting as you know this is acting as a non-inverting input of the operational amplifier. This acting as inverting input of the operational amplifier, output is taken from here. So, that is this is taken as output v 0. Now, for example, if I apply a D C voltage here I apply for example, I apply with respect to ground here. The D C voltage this is plus 15 minus 15, that means, the supply is connected like this and there is the ground and that is the input voltage. So, for example, if I apply here say 2 volt then I connect this to this. Now, you will be surprised that if I give 2 volt here you know if I look at this, I have given now 2 volt with respect to ground.

Then if I look at the output here v 0 this is also 2 volt with respect to ground and this 2 volt will not change even if I change this or I change this or temperature of this temperature of this or temperature of this. Whatever may be the change this will remain 2 volt as long as this remains at 2 volt.

This is what indeed is wanted actually because this was not achievable in the transistor in a simpler way. Now, let us see how first it is. How it is working and then secondly, we see how that you know even with temperature how this is not changing. As well even with varying voltage of this and this how the output is not changing. These 2 points we have to first understand.

Now, for example, if you see the working of these if I give here 2 volt, I know that you know this has to come to 1 .4. Because, base emitter voltage difference is 0.6 so, this is sitting at you know this is sitting at 2 volt. So, automatically I can say this is sitting at 1.4 volt. If this is sitting at 1.4 then there will a current through this now this current partly coming from here and then partly coming from here.

But, however, if I give 2 volts this has to come to 1.4 and there is some current through this. If there is a current through this, there will be a voltage drop across this. Now, this voltage, the voltage across this resistor is actually nothing, but, base emitter voltage of this transistor. Now, we know that this a p n p transistor base emitter voltage had to be only 0.6 for forward biasing. That means, the there is a current and if that current produces voltage of 0.6 volt across this then, that 0.6 volt will make this transistor forward bias, that means this will be start conducting.

So, then current will flow through this so, that means, if I apply 2 volts, this fellow sits at 1.4 that makes the current flow through this and that develops a voltage across this. And that voltage applied across this across base emitter of this transistor that makes this. If the voltage is more than 0.6 then this transistor started conducting and the current is flowing through this.

Now, as the current flows through this voltage positive voltage will start increasing and then this gets more and more voltage. Now, assume that if this voltage at this goes more than 2 volt because you know if I see suppose, if, this is more than two. So, assume that I go to 2.1 then what happens? This is already sitting at 1.4, this is you know this is sitting 1.4, this is 2.1. The difference is 0.7 that is very large because oh 0.6 then enormous current started flowing through the base emitter through the transistor.

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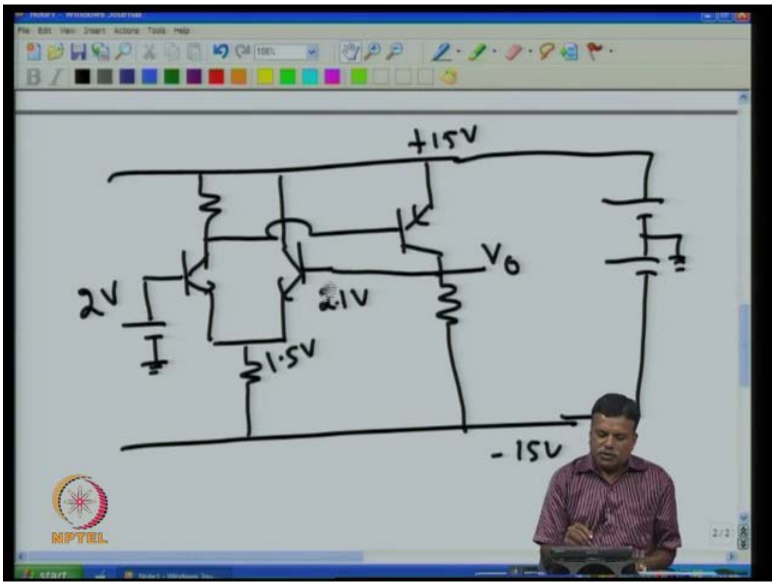

Now, if you assume this is at 2.1 automatically, large current flows through this and that will make this voltage increase. In fact, what happens if it goes to 2.1, this chap is not going to be 1.4. This chap will go to 0.6 less that is this fellow will go to 1.5. If this 1.5, this is 2, it is not good going to conduct. Because, you see this is 1.5 this is 2 only 0.5 volt difference is there. So, this is not going conduct. It is not going conduct, this cannot conduct. If this not conducts, this voltage will decrease. So, automatically what happens once try into go more than 2 volt then, this is all the current trying to come through this and very little current trying to come through this.

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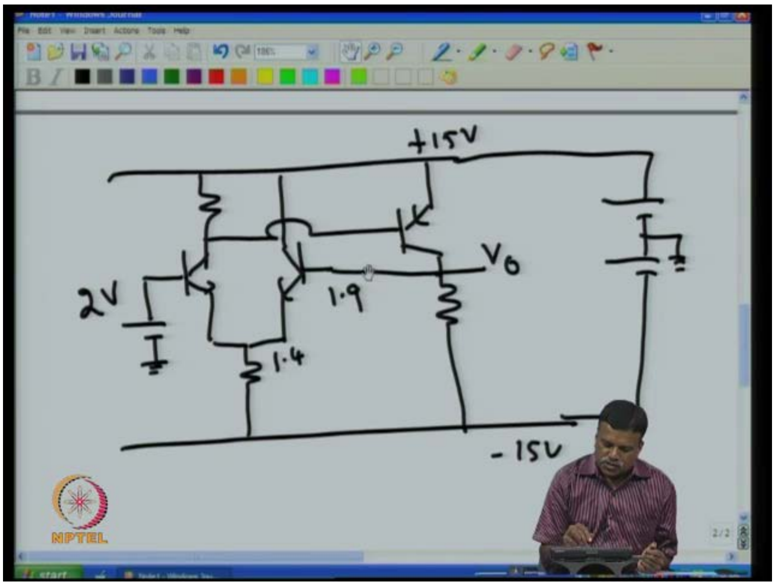

And other way round if this voltage trying to go below 2 volt for example, I take this and put it you know as 1.9 then if this is 2. Automatically, you know, this will go to 1.4 you know this will go to 1.4. If this 1.4 and this 1.9 then, you have only 0.5 and this cannot conduct. Then, heavy current flows through this. You know and this voltage increases. So, automatically you know if this voltage trying to go more than 2, more than 2 volt that is, if this is 2 volt, if this trying to go more than 2 volt then, that makes automatically this transistor conduct less and then it brings backs 2. In case, if this goes below 2, then, again you know below 2 then it makes this transistor to conduct more and brings backs to 2.

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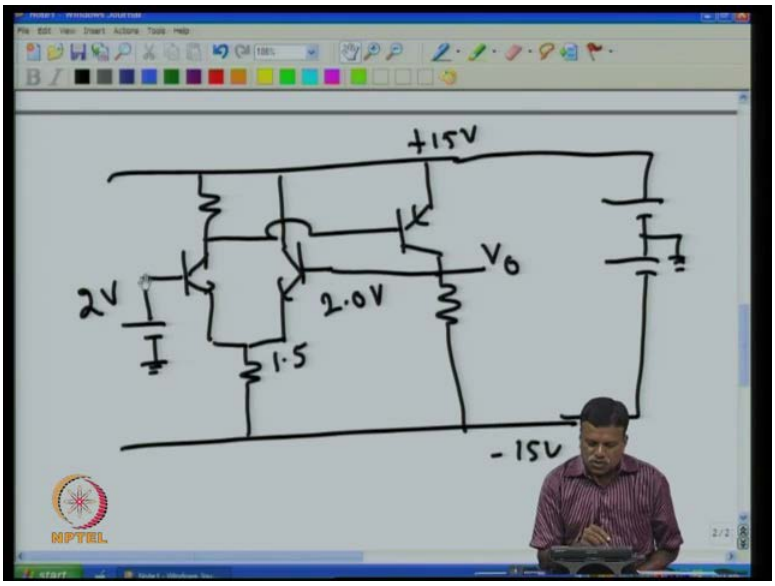

So, it has no other choice other than sitting at 2. So, automatically, that means, that if this is kept 2 then, there is no choice other than coming to 2. That is the wonderful thing because if I fit 2 here then, this also will come to 2.

And if we see what happens when temperature changes even if temperature changes, if this is 2, this also will be 2 only. Because, if temperature changes this base emitter voltage also will change, this base emitter voltage also will change and transistor is very good at tracking. You know they are almost identical. The difference what it comes in base emitter voltage or where second order effect and they are very small.

So, with temperature for example, we know that the base emitter voltage goes by minus 2.2 milli volt per degree C that means, for every 1 degree temperature rise the base emitter voltage will decrease by 2.2 milli volt. And same decrease taking place here you know this also decrease by 2.2.

For example, at 100 degree C or at some other high temperature, instead of at room temperature, I need 0.6 volt here difference. At high temperature assume, I need only 0.5 volt at some other temperature that means, you know if I raise the temperature by 40 degree then I will lose 0.1 volt. That means, at 205 degree if I need 0.6 then at 65 degree I need only 0.5 volt and this also needs only 0.5. So, if it needs 0.5 if I give 2 volt here, this fellow will stop 1.4. All that matter this will goes to 1.5, this need only 0.5. Now, this also needs only 0.5. So, this also will settle only at you know at 2 only because this difference all now only what is required is 0.5.

So, that way the temperature drift you know the temperature change of temperature of this and this has no effect on the output. Similarly, you know this base emitter voltage also will change with temperature. You know it also require only 0.5 at 65 degree, but, then this is not a serious problem because even if it needs only 0.5 and this voltage is 0.6. Then, it will automatically conduct heavily and this voltage will go high.

If this goes high then this will go high and that will make difference small and this will conduct less. So, automatically the voltage will come down. So, this base emitter voltage has only secondary effect and that also is not going to effect the output voltage.

So, this was a remarkable thing because the struggle that we had to amplify D C is no more there. You know we need not worry about the temperature change of this or this.

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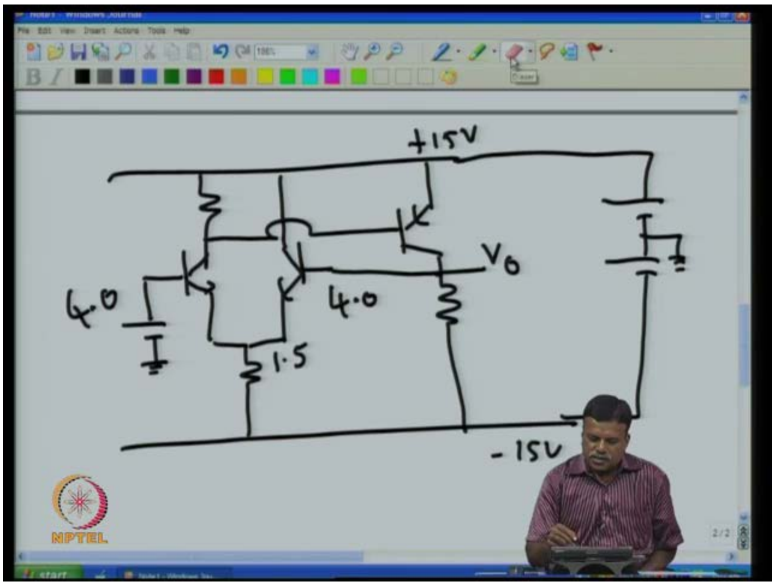

So, if it is 2 automatically it comes to 2. If I keep you know if I keep this is at some other voltage for example, I keep this at 4 volt then this chap also comes to 4 automatically. So, whatever I am giving here that is followed at this point.

Now, I said you know with temperature has no effect. What about supply change? Suppose, supply voltage is plus 15 it goes to 20; No problem If this goes to 20, this trying to also go up. Now, where if the current rate increases more then automatically, the base emitter voltage will increase and that will increase the conduction here and this voltage will go high. If this goes high then this difference increases and this because this will increase then this will decrease. And this current will decrease and automatically if will pull back. So, either this or this, has no effect at the output and that is good because whatever I am giving here that appears here.

But, what is the use? You know whatever voltage you are giving here it comes as it is which has no effect due to temperature or the supply. But, what is the use of getting the same voltage here and here? Because, if at all anything would happen, we want a particularly amplified signal. Then how to amplify the thing that was then very easily? So, what do you do is you have the voltage here instead of directly connecting it here, I will put two resistance here one here and one here to ground.

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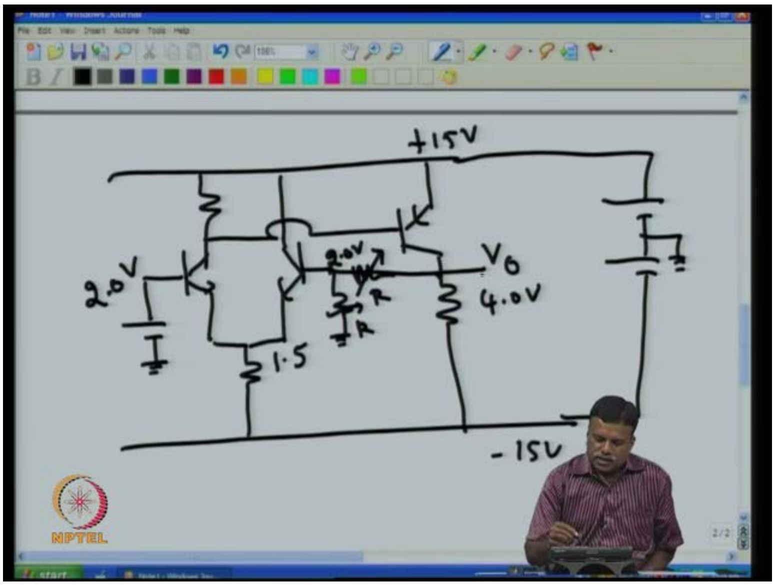

So, if I give here you know 2 volt, I know this has to come to 2 volt. So, this will be 2 volt for example, I put equal resistance here. You know this is R and if this is R; that means whatever voltage is here it is divided by 2. You know assuming the base current is negligible that if I had to get 2 volt here, that means, I had to get 4 volt here.

So, if I give 2 here, this will come to 2 and this will come to 4 volt and that 4 volt will remain constant because this 2 volt will remain constant even if the temperature changes or else supply voltage changes. Because, I had given 2 and this has to come to 2 because if it is not coming to 2 or if it is less than 2, we know that you know less than 2 then this will conduct heavily. Then, automatically the conduction increases and it will go up. So, it adjusts to 2 and this will automatically goes to 4. So, now, we got a gain of 2 I. Given

2 volt then I got 4 volt here. If you want different gain all that I need to do is, I have to only change the resistance here or here if fix the ratio different. Then I will get different gain.

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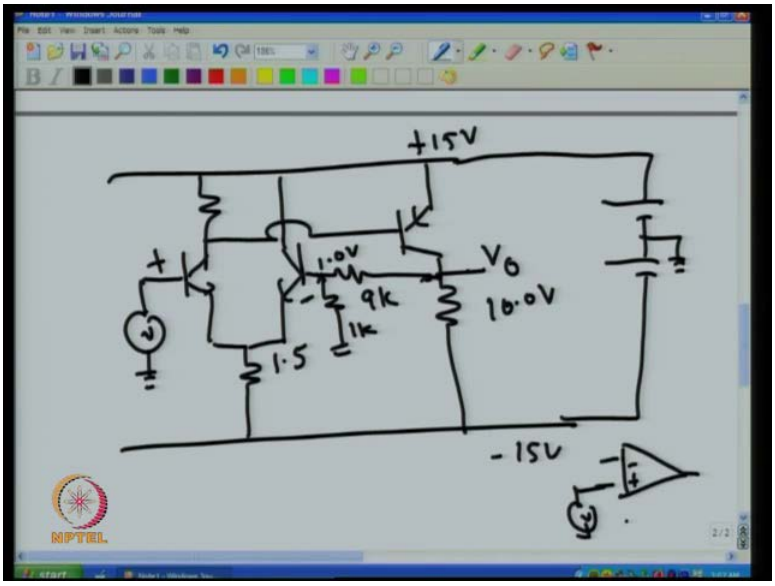

For example, if I want gain 10 all that I should do is, that I remove this and put you know 9 K and 1 K. If I put for example, I put the resistance here 9 K and then 1 K then if I give for example, here I give 1 volt signal input then, this has come to 1 volt. And we know that you know if I have to get 1 volt then, this is the divided by 10 because 9 K and 1 K will make a division of 10. So, if I had to get 1 K I have to get here 10 volt. So, this will go to 10 volt that is gain of 10.

So, whatever gain you want, you can get it by merely selecting this resistance. And this resistance and you know you will get output voltage which is amplified. This is the input voltage that is amplified with a gain that is determined by the ratio of these 2 resistances and the amplified voltage appears here. And this voltage will not change with this or with the temperature and this can be used both for A C as well as a D C not necessary that this only for amplifying the D C voltage.

For example, if I want to amplify A C voltage all that I have do is apply A C directly here. Now, the amplified A C voltage will appear here and there is no biasing work no decoupling required nothing. You give the voltage and take the output here and this was the first operational amplifier developed by Mar Julie and that had solved many problems. It was done during the Second World War and then you know this was handed over as I said to the MIT and then they made it as gun director and it was a successful project. And using this they had hit the incoming aircrafts with 90 percent success rate and that was a remarkable at that time and even in today's standard it is very high.

But, more than that you know this was not termed as operational amplifier at that time. It was termed as operational amplifier later and it was published as, a termed as operational amplifier and then published in a journal almost after Second World War. Then only people come to know about this and they were using this. In fact, this is nothing, but, non inverting timer plus input and this is the minus input of the op amp. You know if I recall the operational amplifier the circuit looks like this. You know we can make it like this plus minus and we give the input and then take the output. You know we are giving the input here I will show you in the next this thing.

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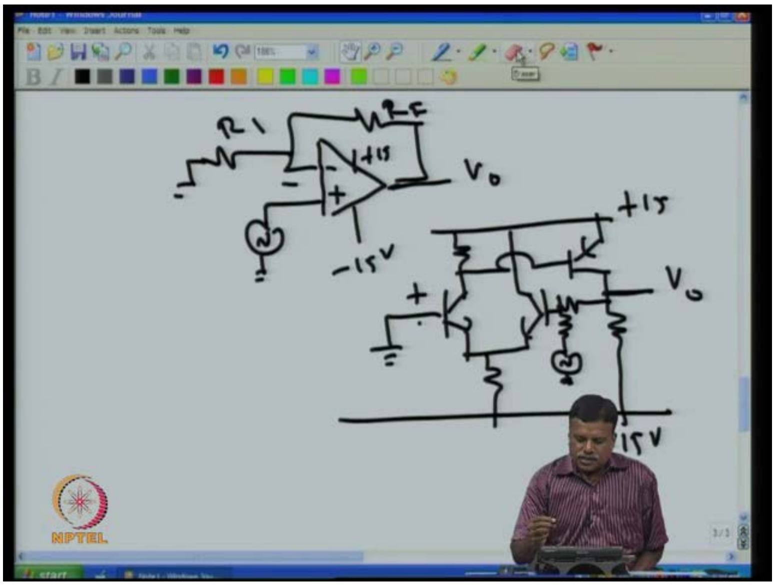

So, this same thing we can show for example, here I show you the equivalent of that and draw bottom to for you. So, you have this and the signal is applied here and if you see what is the circuit which we had discussed so far in terms of this. Now, this plus input is this and we have given the input here to the ground and then this is the minus input is this to this. We have connected 2 resistors this R f and R 1. They are nothing, but, these two resistors this is R f R 1 and this output V 0 that is here and this is plus 15 and that is minus 15 volt. So, we give here this plus 15 and minus 15 volt. Actually, these two this is only now simplified and shown like this.

So, you the gain is now determined 1 plus R F by R 1. For example, if we have put 9 K and 1 K then the gain came 10. So, one can now use this as a building block and then change this resistors to get whatever gain that you want. This was a wonderful thing and it is, obviously, it is big hit and then. In fact, electronics started going after this one only. Now, how will make you know this one if it is true then is it possible to make inverting amplifier in this? Yes it is possible.

For example we want to make a inverting amplifier what I do is, I do not I will not do this one. I will give the ground this fellow then all that I need do is you know do not give the input here. You know the resistance; you have now what you do you apply the input signal here. Now, at this you have two contributions that is one from the signal source other from the output. Since, this is 0; this also will have come to 0. So, what happens is that so, if I if this am 0, this have comes to 0, but, at this.

We have two contributions one from the signal, another from output. So, if this has to become 0 for example, I want in this to be 0, that means, this and this has out of phase 180 degree out of phase. And then the resistance ratio according to the resistance ratio the outputs also have to come in and that is what happens in the case of inverting amplifier.

So, that is birth of operational amplifier. Now, then if it is the case, what is that we can do with this? Because, we had seen about the use of transistor we have seen how the operational amplifier had come in and so on.

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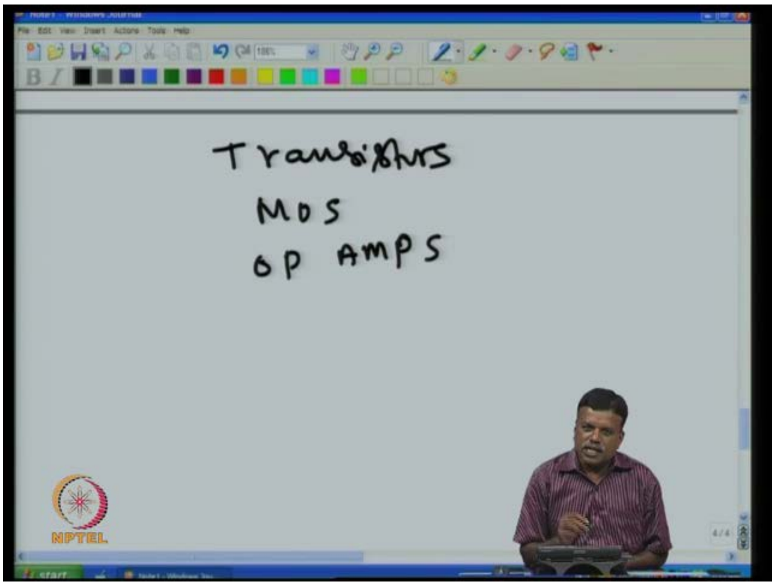

But, then what is that we can do with this transistors and operational amplifier what is that you know we are studying in these analog circuits. Because, if you look at the actual today's use, you know if you look at the electronic instruments we see lot of transistor. Actually what happens is that you will see there are the transistors because then also we see some mos transistors? Then we also see op amps operational amplifier and then you see various resistors capacitors and so on.

Now, all these things to be put together, we have to make a circuit and the circuit supposed to perform given job. Now, connecting these transistors, op amps, resistors, capacitors and then some times inductors all these things put together to perform a given job. It is a not an easy job or not that I can say it is a difficult one. The only thing is you have to understand the rules of the game because you know.

If you have operational amplifier then we should know what is it is limitation? If I use it in a given circuit, you know how much it is going to be useful? How much error this operational amplifier going to introduce? Because, we said you know operational amplifier is a good thing because it amplifies both A C and D C and with temperature as well as power supply to output is not changing.

But, then that is the first order effect, but, if you go very detail and see even op amp output also changes little bit with temperature. So, considering all these aspect we had to design a circuit that will perform the given task effectively. So, effectively we should plan what are the rules associated with the transistors and then mos switches and then op amps resistors capacitors inductors and so on so that we will able to perform the given job accurately.

So, that means, we have to various skills associated with the various skills to be learn. Now, if it is a digital circuit, we have to learn only the logic function logic, how the logic works? And normally we do not bother much about how the internal circuit is working and that is not anymore possible with analog circuit. Analog circuit design involves lot of analytical thinking how to put these components together.

We should know the rules of the game and as well, we also should know how much error going to come in the given circuit. For example, if I design a temperature indicated circuit and if I take this sensor and immerse it. You know for example, I want measure I want to design a temperature indicator circuit.

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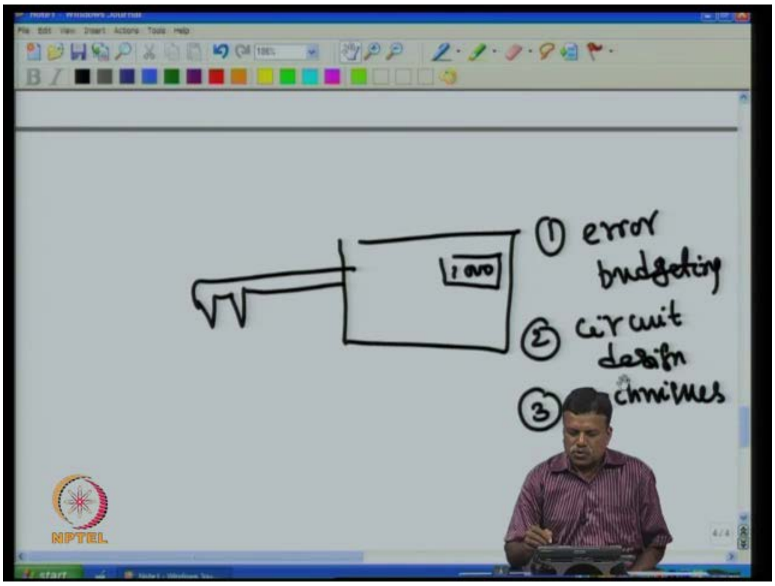

So, if this is my instrument and then I have a thermo couple as a temperature sensor, I connect this thermocouple to the instrument and this fellow going to display the temperature here. But, then this may show this as 1000 degree, but, then is it really 1000 degree? The temperature here difference between in these two point is it really 1000 degree or is it 980 degree or is it 1020 degree or it is 990 degree or 990? What is the error involved? So, one should know you know them so called error or the so called what we call as error budgeting. Because, we had to learn how to do the error budgeting. This is a very important aspect in this.

Then second aspect is how to design the circuit. Here, you know we have to put various components inside and then make it working circuit that calls for connecting various components together flawlessly. And then you should not violate any law and it should work all the time with all that consideration. We have to design the circuit that needs lot of; you know understanding about the basic circuit, without that you will never able to design this thing.

So, it needs lot of analytical thinking. Actually, you need to have lot of analytical thinking. Without analytical thinking, you will not able to design the analog circuit because it is not just logic alone. Say, one given circuit can be designed in different ways and each circuit can give different type of error and then it may cause differently. So, the other aspect is error analytical thinking that is, I should able to synthesize or create a new circuit and that skill one have to acquire. So, I will say that more than analytical skill that the circuit design skill is the one, the second aspects you have to learn.

Then, in fact, third thing is when you are designing a circuit we also have to find whether it is optimum or not. So, lot of new technique is involved which will actually simplify our circuit design. In the sense, not the question of making it very simple, we can arrive at optimum circuit instead of coming a round of way. So, that actually lot of new that techniques we have to learn. That means, if I had to be a good analog circuit designer then I should know about error budgeting. I should have the design and I should have a circuit design skill then, I should aware of various techniques involved in understudy in putting the circuit together.

So, in this course we will try to learn these three aspects; how to acquire circuit design skill and how to make error budgeting and then what are the various techniques involved. These three we will put together basis for this course.

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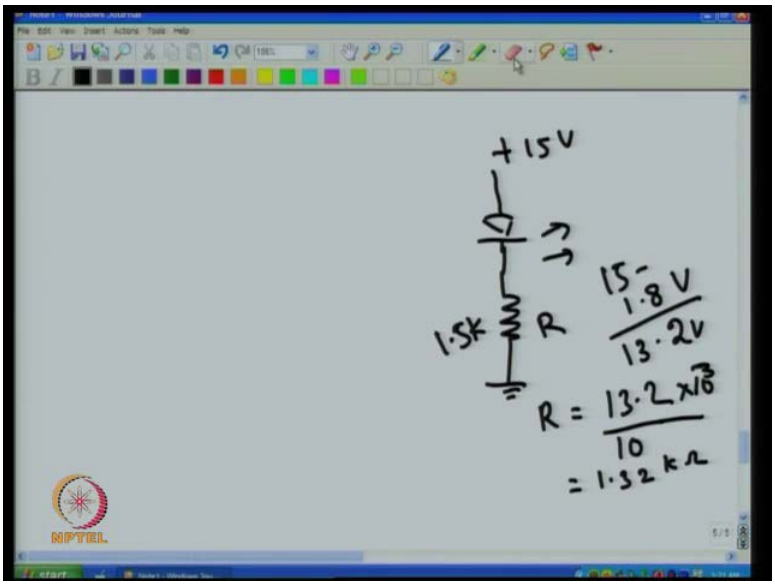

Now, let us see what is the circuit design skill for example, I want make 1 LED to go on and off. I want to use a transistor for that. Then, I will take an LED for example, I have taken 1 LED and I want make this LED to go on off. So, I will give it a power supply. I can assume I have only plus 15 volt power supply and if this LED I want to make this on now. For example, if I want connect; I know that I should not connect immediately to ground.

For example, if I put this to ground then this goes bad because if you look at the basic concept if I apply a voltage LED is like diode and then it is forward biased. During forward bias time, it glows. Then depending upon the color of the LED the current through the LED varies exponentially with voltage. That means, for most of the LED we need to have only 1.8 volt. For example, If 1.8 voltage is there across LED you will find about 10 milli ampere current is going.

if you apply 15 volt, apply now it is 15 volt applied across the LED automatically, it takes very huge current and then this goes bad. That means, I should aware of what is the basic rule involved in connecting the LED.

So, what I do is I will not connect this to ground then I have to somehow make sure that only around 1.8 volt appears across the LED. The rest of the voltage I should make it appear elsewhere. For example, in this case I can put an L E resistance and connect to the ground. So, if you do this, now, the 15 volt is add between these LED and the resistance that I have it here, you know, effectively.

If you are seeing that there is a voltage drop here, there is a voltage drop here, this voltage drop plus this voltage drop is actually 15 volt. But, nevertheless you know I want across this 1.8 and the remaining voltage should be across this. That means, the remaining voltage in this case is 15 minus 1.8 volt that comes 13.2 volt that means, 13.2 volt has to here.

But, we know that this LED needs about 10 milli ampere current for the two glows bright enough. And we should not pass too much current because then the LED also goes bad. So, if I take 10 milli ampere is the acceptable current that you have to get it from the data sheet. In this case, I have taken it as 10 milli ampere then, since, these two are in series and same 10 milli amperes current goes through this.

And if I have 13.2 volt across this, with 10 milli ampere then I need a resistance value the R that actually will be 13.2 divided by 10 milli ampere. The 10 milli ampere goes minus 3 that is, 10 to the power 3. So, that will become 1.32 K resistance.

So, if I put 1.32 K resistance here, then I will see that across this 13.2 volt and 1.8 volt and the LED glows and it will not go bad. May be, the practical value 1.32 K resistance you will not get. So, the acceptable value will be the nearest 1 can be 1.5 K or it can be 1.2 k. So, or even it can be, say, if we want take it we will put it 1.5K the current will be little less does not matter because, we have no other choice. The nearest resistance that is available is 1.5 K, I can do this. So, we have to, if I want make the LED to glow for example, we have to calculate these things and this type of calculations we will be encountering in analog circuit very often.

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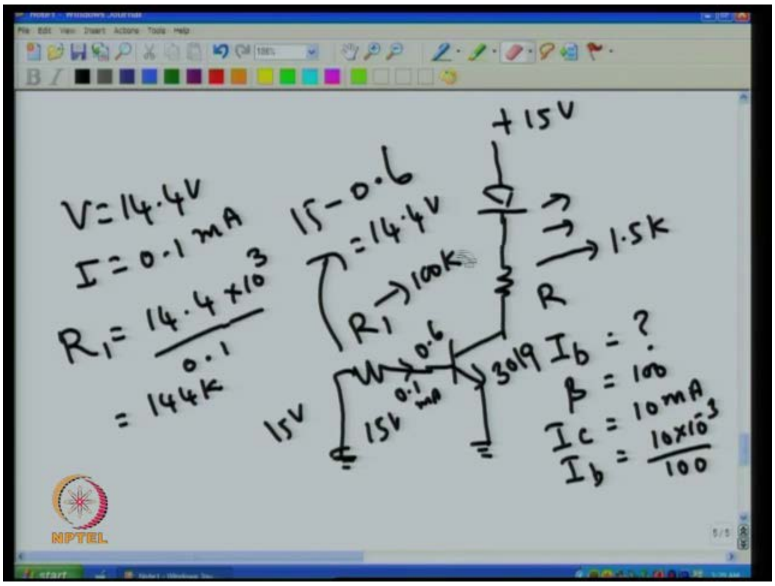

Now, let us see how to make LED to go on off using a transistor for example, what I can do is now I want make the this LED go on off using. So, what do I do? I remove this, and then I connect this. Then I connect the transistor here for example, I can use transistor in this case to switch on and off. Connect this. Now, if I want to make the transistor on I give a voltage here in the base. If I give a voltage at the base, then there will be a current in the base circuit.

For example, there will a current here then there will be a current here. So, then LED will glow if sufficient current flows through this. Now, we want a 10 milli ampere current through this and then this is the transistor current you know. The question is how much voltage I have assume that I have here another same 15 volt supply is here. Then question what resistance I have to use here say R 1, this is the resistance which we had decided that is actually 1.5 k.

Now, what is the resistance value R 1? I have to select because we had fixed 10 milli ampere current through this. If 10 milli amperes current have to go through the collector circuit, we know the base needs some current. The base current you know that I B is how much? What is the base current we have to find out now? To know the base current, I should know the beta of this resistor. Assume the beta of transistor is 100. So, I see the collector current is 10 milliamps. So, the beta of the beta is ratio between these two. So, automatically I B comes your I c that is 10 milli ampere divided by 100. That is you will have only 0.1 milli ampere current flowing here. That is this current is 0.1 milli ampere. So, 0.1 milli ampere current it is 100 times amplified and then 10 milli ampere current is flowing through this and then the LED glows. So, I need 0.1 milli ampere then, the question is what is the value of R 1 I have to select?

Now, we know that this is you know this point is 0 and then we know this have sit at 0.6 because base emitter for forward bias we needs 0.6. So, this is 0.6 so, this is 15. So, voltage across this resistance is 15 minus 0.6. So, that is 14.4 volt. So, we have voltage across this resistance out be 14.4 volt because this has no other go other than sitting at 0.6 because, if it less than 0.6, it will not conduct.

If there is no conduct, no current then, if it starts conducting there is no base current then automatically, there would not be any voltage drop. So, once you connect like this will automatically come to 0.6. So, that makes this fellow to get 14.4 volt. If it is 14.4 volt and then we know that what is the required current is 0.1 ampere. Then what is the R value I have to put?

So, you have this voltage is actually 14.4 volt and then the current is actually 0.1 amps then the resistance R that can be calculated that actually that should give this one 14.4 divided by this 0.1. So, those 0.1 milliamps sorry this is 0.1 I is 1milliamps. So, if I take milliamps here that actually makes 10 power 3. So, that comes 144 k. So, the if I have this R 1 that is R 1, I have to need 144K that will make sure that 0.1 milli ampere current is flowing through that. Now, if I see the nearest available value is 120 K resistance available or I can have 100 K because the current goes more than 0.1. No harm what is required is 0.1 milli ampere current minimum.

That we make sure here 10 milli amperes current is flowing and we are using the transistor as a switch we are not operating it in the linear region. So, if we send anything more than 0.1 milli amperes that is no problem. So, if I put 144 K you will have 0.1 milli amperes current. If I put 100 K little more than 0.1 milli ampere current, that is good; no harm. So, you can select this R 1 is a practical value 100 k.

So, whenever this 15 volt supplied LED will glow, if this 15 volt is removed and I connect it to ground. You know for example, I will put this 100 K here and then connect to this ground then the LED goes off here. You are using this transistor as a switch because in the analog circuit course you will be using the transistor or misfit as switch at very many times.

So, it is essentially that we hour of these calculations and importance of this by. Many of them have a doubt that, you know if I need 0.1 milli ampere, I have to give only 0.1 milli ampere. It is not true then you should not give less than 0.1 milli amperes. If you give more than 0.1 milli amperes, it is no harm. Even though it is a waste of current, but, it is not a serious problem, nothing happens, the transistor works well. In fact, it is better nothing wrong so, more than 0.1 milli ampere. So, instead of saying0.1 milli ampere we say we need more than 0.1 milli ampere.

Similarly, if I look at beta we had taken beta as 100, but, then if you look at the data sheet of any transistor for example, here assume that I have used 3 0 1 9 transistor, we will say the beta of the transistor is minimum 100. That means, I had taken as 100 here, but, in actual case the beta of the transistor, actual transistor what we had used even in 3019 1309. If I take it may have beta of 100, another 309 may have beta of 150. When I say beta 100 it is the minimum value 100 no 309 will have less than beta 100, but, anything more than 100 is you have to accept it.

You might have a transistor 3019 with beta of 200 also. You may get it when you buy 100 numbers 3019 from one particular company or 1000 numbers you buy. In fact, most of them will be 150 200 like that only. Very few will be close to 100 then, but, nevertheless none will be less than 100.

So, in this case we always take the worst case parameter that is required. Because, if I assume beta is the 100 is here in this case, we had taken beta is 100 that is the worst case value. So, if I design with beta 100 then no problem any transistor you put it will work because if the beta is more then I need only low current, but, anyway I am giving more than required. So, no harm it works as a switch. So, this is another important concept we have to learn. Analog circuit design that we always going to design a circuit for the worst case taking the parameters which are you know worst for that particular case. So, even if I use different transistor it is not going to affect.

That is why, it is not necessary. You know, if I valued at 144 K, there is no in looking for 144 K resistance because the natural case the anyway whatever transistor is used that beta need not be 100 that going to definitely different going to be more than 100. So, there is no in calculating the resistance. So, accurately and putting it there that has no real meaning it is only academic interest. So, this should be kept in mind when using the transistor.

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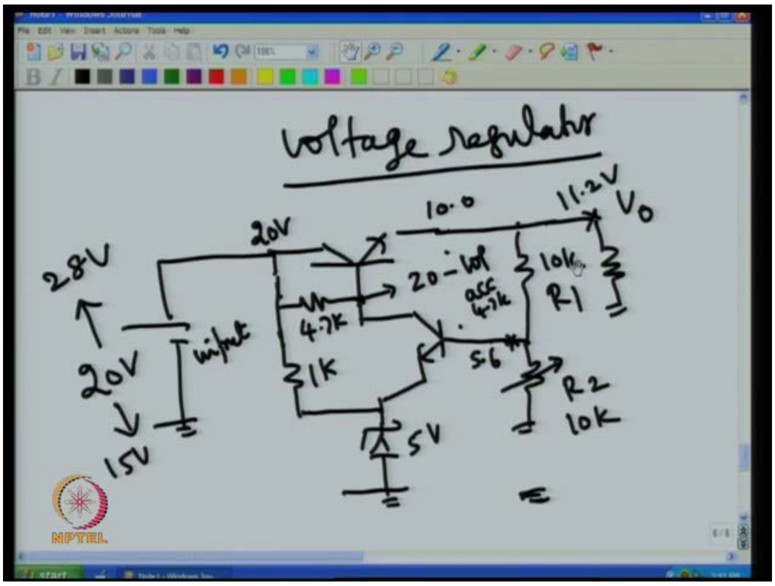

Now, let us see what are the other things they had done using the transistor earlier? Before operational amplifier had come in now for example, see other application that using transistor done was voltage regulators. For example, we might have seen transistor as a voltage regulator. In fact, voltage regulator was designed much before transistor came in you know using vacuum tubes only the first voltage regulator had come in. In fact, it was published in journal of physics c in 1930, voltage regulator using vacuum tubes. But, here I will show you how to design the how the voltage regulator was designed using transistor very primitive regulator.

For example, what they had done was they had taken transistor like this. Then, they had put the resistance here then the so, called error amplifier was built in here. They put the sneer diode here and that is the input voltage which is unregulated. It is the unregulated input and then I have these two resistors connected to this and that is the regulated output. So, the V 0 is the regulated output and then to bias another resistance is put here.

So, this is the for example, assume that this is 20 volt D C and this is unregulated. Unregulated in the sense, this voltage may be varying. Say, 20 it may go up to 28 down it may come to 15. Assume that this is the case, so, this voltage can be anywhere from 15 to 28, but, what I want here is the output to be steady 10 volt that this circuit does.

Now, if you look at it how it is working? Now, this is a zener voltage, zener diode. Now, if I for example, I can remove this. That is, I put only this. Now, this is nothing but, biasing the sneer. So, now, there will be a current through this, that will flowing through this sneer assume this is a 5 volt zener. That means if sufficient current flows through the zener, this will set at 5 volt.

It will be always 5 it will not change. Then it will not change, this will be only 5 volt. Now, how much current I have to pass to keep this one at 5? If current is low, it will go below 5, but, it will nevertheless it will go it will not go more than 5. So, I had find out from the data sheet of the sneer what is the need current of the zener to get 5 volt.

Say for example, assume that it needs 10 milli ampere current to give 5 volt. So, as long as 10 milli ampere current goes through that it will be 5 volt more than 10 goes, then also it going to be 5 volt. So, I know that this voltage going to be minimum 15. It will never go below 15 volt. So, what I do is this is 5. So, I need to have there will be a minimum of 10 volt that is, even in when the voltage if it is 15 will be a 10 volt across this. So, if I take here 1 K for example, here, if this I take voltage across.

If I take this as 1 K then, I know that when this is 15 volt this is 15 and this will be 5 and then 10 milli amperes current will be going. That means, 10 milli ampere anyway gives 5 volt. So, the voltage across this will be 10 and that will ensure 10 milli ampere current even in the worst case. Of course, the voltage goes 28 more current will go, there is no harm, the zener voltage will slightly increase little more than 5 and at this point of time we take it is only 5.

So, this is only biasing the transistor. These two resistors you know, this I take R 1 and R 2 they are only voltage divider. You know whatever output voltage there that is divided and at this point, you get the divided voltage. Because, if it is for example, if I put here 10 K and here also 10 K then, I know that if it is 10 volt I will get 5 volt here.

So, R whatever voltage here, half of that voltage will come here. Now, I give at this point now, I add the transistor. All that I do is that, I connect this here and connect this here that becomes a voltage regulator. Now, I know that this is sitting at 5. Even if this current goes also this always will sit at 5. Then I had one more resistance here. So, this is always at 5. Suppose, the output voltage goes more than 10 then, this will go more than 5.

Then assume this is gone to 5.6 because if this is at 5 if the transistor have to conduct this has to come to 5.6, because unless it comes to 5.6, it will not conduct. So, essentially what we are trying is, if this is sitting at 5 and then this cannot go more than 5.6. Suppose, if it goes more than 5.6, then the heavy conduction will take place then heavy current will flow through this that current actually comes through this it goes through this.

So, increasing current through sneer not going to increase this voltage, this will sit at 5. So, if it goes more than 5.6, why it goes more than 5.6? Because, this goes more than 11.2, because more than twice it goes then the 11.2 means you will get 5.6. If it goes more than 11.2, this fellow will go more than 5.6. If it goes more than 5.6, then what happens? This will conduct heavily. That current actually comes down here because this cannot give any current; this can only current can flow here.

So, the heavy current will flow through this. When heavy current flows through this, there will be a heavy voltage drop across this, that will make, you know this voltage decrease. Because, after all voltage at this is what you have this voltage assume this is 20 volt sitting at any given time 20 volt. And then if you put here for example, 4 K, I say 4.7 K resistance then, if 5 milli ampere goes, you will have 20 volt drop. That will make this fellow 0. If 1 milli ampere current goes through this, then you will have 4.7 volt drop. That means, if it is 20 here. 4.7 volt drop will make me to get 15.3 volt here. If 2 milli amperes current goes through this, then you will have 9.4 volt drop across this and then you will have 20 minus 9.4 that will come.

So, voltage at this is nothing, but, 20 that is supply voltage minus voltage across this across 4.7 K voltage across this depends on how much current it is flowing. So, if more current goes through this, there will be more voltage drop across this. And you will have less voltage here, but, whatever voltage is here that voltage appears here with less by 0.6. So, if this is assume this is coming either come to 10.6, then this will automatically come to 10 because, the base emitter voltage has to be only 0.6. So, if it is 10.6 this come to 10 if it is 20 this will come to 19.4.

So, essentially what happens if more current flows through this for example, this voltage will be more than 5.6 then more current flows through this. That will make this voltage decrease, that will make this voltage also decrease then this also will decrease in case, if this goes less than 5.6. Because, this is sitting at 5, it will go less than 5.6, then this will not conduct or the current flowing through this is very small. Then less voltage drop occurs you know across this you will have small voltage drop across this.

That means, more voltage will come here. Other way, around, if this goes less than 5.6, less current through this and more voltage at this. Then voltage will go up here also. In case, if this goes up and this also will goes up. If it goes more than 5.6 then again the conduction will increase and this voltage will decrease and this will decrease.

So, eventually if it is set at 5, this have to sit only at 5.63 is no other go. If it tries to go up, immediately, this decreases and then this decreases. If it is goes below 5.6 immediately this will go up and then this also will go up. So, automatically, if I set 5 this will sit at 5.6. If this sit at 5.6, I know that voltage across this 5.6 means the base current is negligible. So, this current and this current are same so, across this 5.6 means, across whatever voltage there, only here across this also 5.6. So, you will get voltage of 5.6 plus 5.6 that is, 11.2 volt it will come and 11.2 volt is what it stabilizes here.

For example, I can vary this resistance R 1 R 2 for example, I vary this resistance then I will find voltage is changing, but, nevertheless this 11.2 will always remain constant. Whether I put a load here or I remove the load, whatever it is, if I am not changing this for example, if I put this and this equal then I will get 11.2. Suppose, if I change this of course, it will change and it is you know good example of showing how the transistor was working.

In fact, transistor was used as a voltage regulator and then this is a simple voltage regulator using transistor and we can get a regulated output. Of course, it is not a very good regulator; if I change the load output will not be strictly 11.2. It will be slightly changing. Similarly, if I change the supply voltage the output voltage will not be 11.2 exact, it will also slightly change. That is because, the 0.6 volt what we had taken is not absolutely true. That with you know for various reasons, this voltage can slightly change.

For example, if temperature increases this 0.6 requirement decreases. You know at 65 degree it will be only 0.5 degree, 0.5 volt requires. So, if this is 5 then this will come to

5.5 and output will go to 11. So, with temperature also, output will change a little bit. In fact, if I increase the supply voltage then, this voltage will go high and if I have to keep to 11.2 then we may need more current flow through this because, if it is 208 then you need more voltage drop across this. If it is 30, if it is still 11.2 then you need nearly 20 volt across this. If input is 15 then if it has to be 11 then it is 4 or 5 volt. So, current that has go through this have to change then only this will change. If more current goes through this then, you need more base emitter voltage difference. That means this if more current have to go instead of 5.6 may go to 5.61 or 5.62 and that will make this voltage also you have to increase.

So, that way with supply increase this also will call for this also will go up little bit. So, like this some drawbacks, but, nevertheless for as a regulator it is a good one. It was extensively used in earlier days and then in fact, even today we use these regulator the regulation requirement is not very tight.

So, we had seen about transistor usage and then also we had seen how the op amp born from transistor and what were the drawbacks of the transistor. Drawbacks of the transistor were the voltage drip and then voltage change due to supply voltage variation. These two were eliminated by using the operation amplifier that was done by Julie. Then also, I had shown you this time how to use the transistor as a switch and how to use transistor as a voltage regulator.