Circuits For Analog System Design

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Lecture No. # 01
Transistor Amplifier

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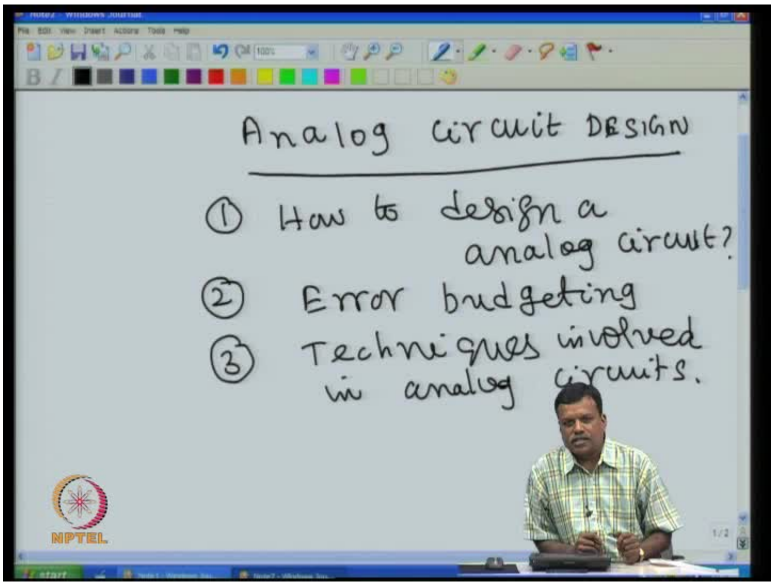

In this course, you will be learning about analog circuit design. In this course, we will concentrate on three aspects: one is how to design an analog circuit, then the second aspects is, you will also concentrate on the so called error budgeting and then, thirdly, we will also concentrate on various techniques involved in analog circuits.

So, these three are very important in analog circuit design. Now, if you look at, it look as analog circuit design. What is that involved? It is basically putting transistors, op amps, resistors, capacitors, and diodes and so on, various passive components and active components you will put together and make a circuit.

Now, if analog circuit design is partly arch, partly science actually, because you need lot of analytical thinking put together these components in a working manner, so that you will get there desired results. This designing analog circuit needs lot of analytical thinking and a lot of experience as well; so, you had keep doing many circuits, then only it will come to you.

Then, the second accepts is when you are designing a circuit, for example, you design temperature controller circuit or temperature indicated circuit; when you are doing that, it is essential that you should know whether the desire accuracy is achieved in this circuit or not.

For that, you should understand what are the various errors involved, then how to compute the various errors and then, finally put together what is the total error that expected in the circuit in the worst case scenario, because in analogs components what happens is that you have op amp, but then if I take 741 op amp, that whatever the error that you are getting depends upon the particular pieces of 741 that you are using. For example, with I say offset voltage drift, offset voltage drift is not same for all the 741's; you know the maximum value and you know the minimum value.

So, while designing, we have to consider what is the worst case error that is the expected. Once we know it, how to compute these errors for a given analog circuit, that we called as error budgeting; this we will concentrate very much in this circuit.

Similarly, we also should know various techniques involved. For example, if I am measuring a capacitor, then I just following the basic principle of capacitors measurement is not enough. We should know what are the various techniques already existing for the measurement of the capacitance, so that there no stray, stray capacitance not involved and so on; that kind of things are must. So, we also should know various techniques involved in designing analog circuit.

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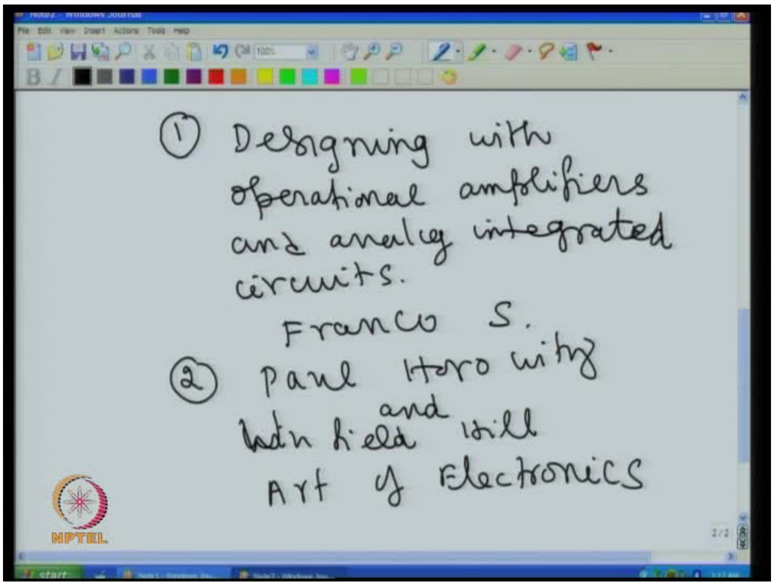

So, these three things we will be concentrated in this course very much. The problem in analog circuit design is that you do not have very many books concentrating on actual circuit design; you have books on error budgeting. And techniques involved also you do not have many books.

However, these two books what I am going to give here, it will help you somewhat in understanding this course: one is designing with operational amplifiers and analog integrated circuits by Franco S - this book is good for the error budgeting; and the second book actually is by Paul Horo Witz and Win Field Hill - this topic is art of electronics.

So, these two books are good for you for reference. And the first book: the Franco S is actually gives you a lot of information about error budgeting and this art of electronics gives you a lot of information about circuit design techniques.

So, this is about this course. Now, we will first see, what is the background that you need to learn this course. I will just taught with transistor amplifiers and then, what is the issue involved in that. And from there, how the op amp is coming, then we go ahead from there on how to design the circuit.

Basically, I will expect you, you have some knowledge about basic working of the transistor and then basic working of the operation amplifier, then how to use resistors, capacitor and so on, and the basic Ohm’s law. These are the background materials let you have to have and you should have to learn. Without that, it is not possible to understand the course, but however, I will repeat these things little bit in the beginning, so that I will able to follow the course.

Now, let me start with transistor amplifiers, because you are all familiar with transistor amplifiers in your undergraduate course. However, I will repeat this, so that there is continuity in this.

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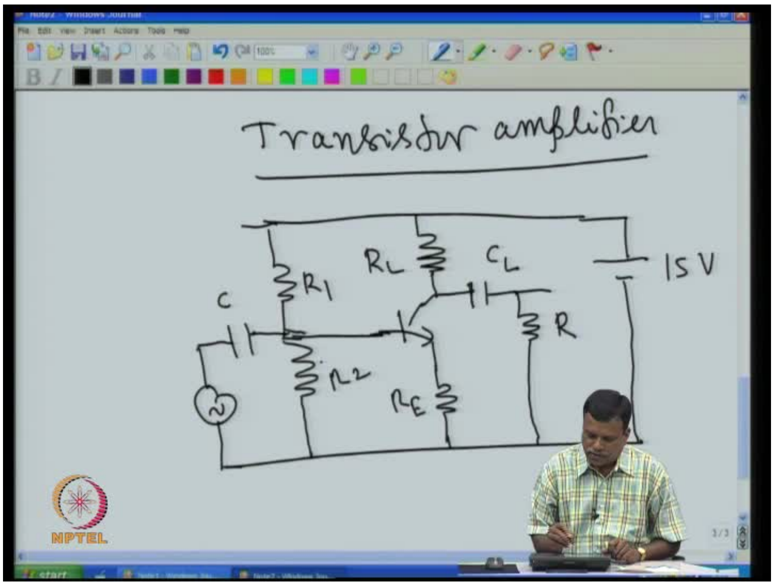

So, if you take the transistor amplifier, the transistor amplifier circuit if you look at it, it looks like this (Refer Slide Time: 08.22). For example, you take n p n transistors, then if you look at the amplifier, that looks like this. You have a power supply here and then you have one resistance connected at the groundside, then you have two biasing resistors that is connected to this one and then to the input, we apply the connect the AC source.

So, you have the supply is connected here, essentially you have a DC source connected here. So, assume that this is around 15 volt supply, we have connected the positive to this. And then, we name the resistors, you have R L, you have R E, this is R 1 and name it as R 2, then you have the capacitors c and this is the signal source - AC source (Refer Slide Time: 09.25).

Our aim is we want to amplify this signal and then amplified output supposed to appear here. This amplified output, I will take it through a decoupling capacitors and that is the low resistor across this and you will get the output; so, these capacitors, I will call C L.

Now, this circuit is familiar I hope for most of you, because already done some basic course in this. Now, the my aim for looking this circuit is the first example is that we get understand what is the problem associated with this, from here on how the analog electronics at grow on to the present day status.

Now, you look at the circuits, basically this input signal is amplified and the amplified voltage appears here. Now, what is the basic philosophy involved in using the transistors? Essentially, we had to forward bias the base-emitter junction and the reverse bias the base collector junction.

Now, if we take this voltage - 15 volt, actually, that is divided between R 1 and R 2, because R 1 and R 2 is acting as the voltage divider. For example, if I forget about this one, then, for example, I remove this, then I remove this, now this is nothing but voltage divider(Refer Slide Time: 11.09).

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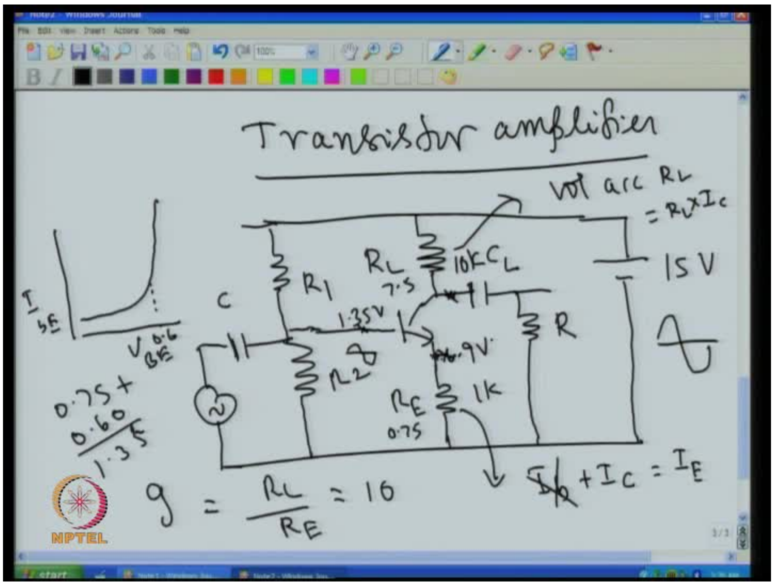

So, depending upon R 1 value and R 2 value, you will get the voltage at this point. Now, what I do is, I will now redraw this. For example, if I have this is 10 k and this is also 10 k, then I will get half the voltage, where I will get 7.5 here (Refer Slide Time: 11.31).

So, I can select of course any values, so I assume that I put R 1 and R 2 are equal start with, so I will get 7.5; then, I connect this 7.5 to this point. Once if I connect to the base, that means, base is at 7.4 - assume 7.5, assume that the base current is negligible. In that case, automatically this emitter will come to 6.9 volt (Refer Slide Time: 12.05). This is because, we know that for any appraisable conduction, we need base-emitter voltage difference of 0.6 and this is a very important assumption that we have to remember and we will be using this at very many places.

So, the base-emitter voltage difference in the forward bias condition will always be around 0.6, if the transistor actually be in a useful working range. In the voltage less than 0.6, then you will find very very little current is flowing even in the collector. Normally, you will never find above 0.6 volt across the base-emitter, because above 0.7 voltage is there or if you apply above anything more than 0.7, you will find enormous current is flowing in the collector circuit.

That is why, we take this 0.6 volt as the reference level in any transistor for the forward condition; so, this way we using throughout this course. This is coming because the forward biasing of the base-emitter, you know, if you plot this base-emitter current you know base-emitter current verses V B E - base-emitter voltage, that actually goes exponentially like this. So, 0.6 is somewhere here; above 0.6, you see very high current. So, essentially we can assume that always if I give some voltage here and emitter will be 0.6 volt less. That is why, here I give 7.5 and assume 6.9 (Refer Slide Time: 13.40).

Once this is assume, then if I know the resistance value, then I know this current where this is 6.9; I know the resistance value, so this current is known. Then, all we know that the collector current and emitter current are almost equal, because you know that ideally speaking, the emitter current is collector current plus base current. So, this current consist of I b plus I c that is equal to I e - the emitter current (Refer Slide Time: 14.18), but then I b is very small compared to I c, so we normally take collector current is equal to emitter current. I know the collector current, I know the resistance value of this, so I can find out what is the voltage across R L. So, voltage across R L, voltage across R L is actually comes to be this resistance value into I c.

So, once it means, if I know the base voltage, then immediately I can write what is the emitter voltage, then immediately, I can find out what is the current through this resistance. Once I know the current through this resistance, I know the current through this, then I know the resistance value, so I know the voltage across this (Refer Slide Time: 15.13). If voltage across this is known, then immediately I can write what is the voltage across the collector, because this is 15 and if this voltage is 5, then I know that this voltage is 10.

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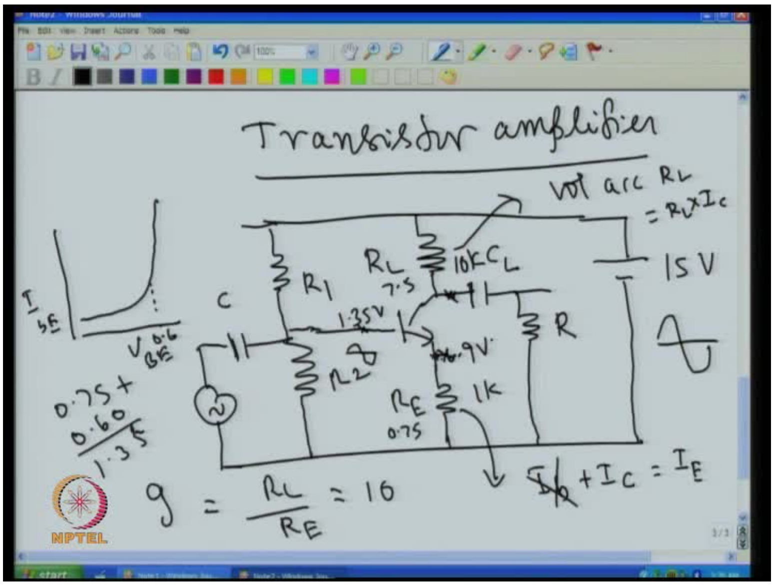

So, that means, once I know the base voltage, I can write what is the voltage at this point, what is the voltage at this point (Refer Slide Time: 15.33). This is very important thing, because we had to know what is the voltage that you expect at different points - particularly at emitter and collector.

So, if I want use this circuit for amplification, then I should know how much resistance I have to keep this, how much resistance keep here or other way, around what is the voltage I have to keep it here; in this example I just taken 7.5 (Refer Slide Time: 15.48).

So, what is the ideal voltage that I had to keep at the base. Now, ideally speaking, you know I am taking the output voltage from the collector, so the output voltage, it will be AC; that means, the voltage will go up and then come down. If it is sine wave, then the voltage will go up and come down. So, if I want equal swing, ideally keeping these are 7.5 is best. So, I keep this at 7.5, then it can go up to 15 and also come down at lower side. So, we try to keep this in the normal case; without any AC signal, we try to keep it at 7.5 (Refer Slide Time: 16.38). So, how to keep this at 7.5 and then, also we had to decide what is the gain that we want. Assume we want gain of 10, if you want gain of 10, then this rises the R L and R E should have ratio of 10, because you see whatever voltage I am giving here, for example, if I give an AC voltage through this capacitor, I apply an AC voltage through this capacitor to this point, now at this point you will get the DC voltage plus this AC voltage - both are added together and coming. So, if you take this one, so voltage at this point will be this AC plus whatever the DC voltage that is given by this R 1 and R 2 (Refer Slide Time: 17.24).

So, this voltage will be amplified and then coming at this point, but we know whatever change that happening here, that have to happen here as well, because of this and this are differ only by 0.6. If it is at 7 volt, then this will comes to 6.4; if it is 8, then this comes to 7.4. So, basically viewing that initial difference of 0.6 at any time, whatever change that is happening here, that is happening here (Refer Slide Time: 18.05). That means, if I give a signal AC signal here - if signal appears here - the same AC signal will be appearing across this resistance.

So, if the signal is 10 millivolt, then you will see that the 10 millivolt automatically comes across this resistance R E and we know that this current same as this current. So if the signal voltage is 10 millivolt, the 10 millivolt voltage is seeing appearing across this along with the DC (Refer Slide Time: 18.33). Then, automatically the AC - that 10 millivolt AC - produce varying current here, that also we will produce the varying current here; so, you will get AC automatically. So, the AC voltage will be more, if the resistance more; the AC voltage is less, if the resistance is less.

So, basically the gain is determined by the ratio between R L and R E. So, the gain of the circuit is actually given by R L by R E; so, if need a gain 10 for example, then I have to make sure this ratio is that of 10. Now, for example, I can take this is 1 k and I can take this as 10 k, then I can expect gain of 10.

You fixed this one and then you have fixed this one, now we have to fixed this R 1 and R 2 (Refer slide Time: 19.30). Now, if it is 1 k, then if I want keep this one at 7.5 volt - that is the midpoint of the power supply, because the power supply is 15 volts - I want keep this at 7.5. Then, if this voltage is fixed, then automatically this voltage across this is fixed - that is 7.5.

The voltage across this is 7.5, then since the same current is flowing through this, voltage across this will be 0.75; because the voltage across this is 7.5 - the ratio is 1 is to 10 - this current and this current are same, so automatically the voltage across this has to be 7.5, that is a DC voltage. 7.5 will be there. If this is at 7.5 volts, then this automatically supposed go to 0.6 extra; that is, 0.75 plus 0.6 is equal to 1.35 volts; so, this will be 1.35 volts.

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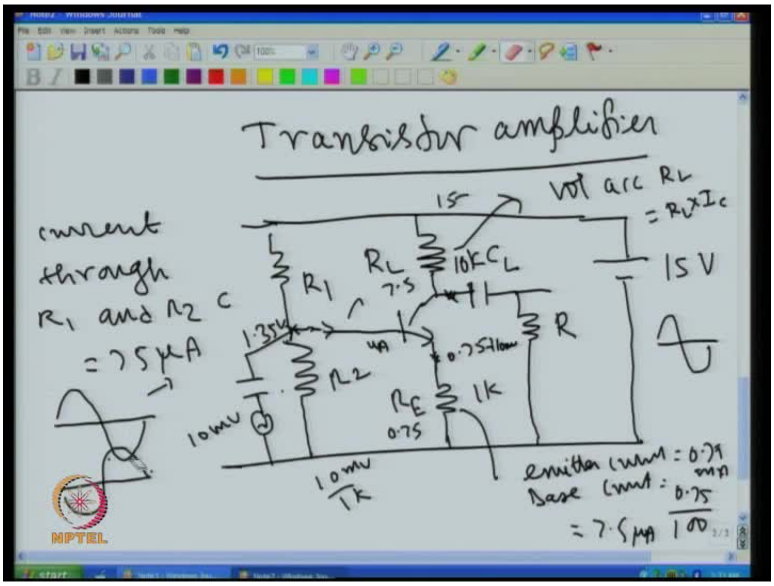

So, if I keep this one at 1.35, this will come to 0.75, this will come to 0.75. Then, if this is 0.75, then the current of 0.75 milli ampere is flowing. The same 0.75 milli ampere goes through 10 volt, that will produce 7.5 volts difference across of this, that will make this point sit at 7.5. So, all that need to be done is I have to keep this at 1.35, that will make this fellow sit at 7.5 and then this fellow sit at 0.75 (Refer Slide Time: 20.58). That is assuming there is no AC signal. You assuming there is no AC here, then I want bias this, I remove this, so this is 10 k, I want keep 7.5, then I have to keep here 1.35. Now, to keep 1.35, what is the values I have to select for R 1 and R 2?

Now, originally, we assumed the base current is negligible. We can continue to assume that, but actually we know this current is voltage 0.75, this one case current of 0.75 milli ampere is going and then automatically we can know the base current, because this emitter current and base current differ by h f e time - that is, beta time.

If I take for this transistor beta is 100, then if this is 0.75 milli ampere, so base current is 0.75 milli ampere, so base currents equal to 0.75 milli ampere, emitter current is 0.75 milli ampere; that means, base current will be 0.75 milli ampere by 100; here we are taking 100 as beta of the transistor, so that will give you around 75 milli ampere current at the base, because 75 micro ampere that is coming as, 100 actually 75 will be 750 divided by 100, 7.5 micro ampere current. So, this base current comes, it have to be 7.5 micro ampere. So this current is 0.75 milli ampere, this turns have to be 7.5 micro ampere (Refer Slide Time: 23.17).So, actually that is a small current through this.

Now, we select this current more than this 7.5 milli ampere to make it - this current has no effect on this voltage division, I fix this current 10 times more than this. So, I fix this 75 micro ampere for this. So, essentially if I see this, Now, I need current through R 1 R 2, current through R 1 and R 2 R 2 will be 75 micro amps; that is, I taken 10 times more than the base current. So, I know the current through this, I know the voltage at this point what is the required is 1.35 volts, so 1.35 volt and then I know the current through this, so I can select this resistance and then I can select this resistance as well (Refer Slide Time: 24.18).

So, these R 1 and R 2 can be selected that way. Now, once that is selected, then we can apply the voltage because we kept this one at 1.35. Now, I can apply the voltage here - AC voltage - through this capacitor; this actually blocks this 1.35 volt from getting shorted. So, this capacitors requires, but this AC goes through this and that is applied across here. Then, you will get, whatever suppose if I put 10 milli volt here, the same 10 milli volt - that is, 7.5 plus this 10 milli volt comes here and that produce the AC variation across this (Refer Slide Time: 25.04). The same variation taking place here and then you will get 10 times amplified voltage at this point.

Now, this type amplifier is very popular and all that you need to do is that, you select these resistors correctly. That is, for example, you want 10 gain, I put ratio of 1 is to 10, then you get the amplified by affecter of 10. We also know that when the voltage increases here, for example, when the input voltage is goes up like this, then this also will go up - at this point by equal amount (Refer Slide Time: 25.45). Suppose, if this goes up by 10 milli volt, this also goes up by 10 mill volt. Then, the current increase will be 10 milli volt divided by 1 k, that is the increase in current.

Similarly, when the AC voltage goes down, this current will also decrease by the same amount. So, here also the current increases where in same amount and then decreases in the same amount. That is, when the voltage is increasing at the base, this current is increasing; when the voltage decreasing, this current is decreasing.

Then, if you look at this point, then when the current is more, you have more voltage drop. So, voltage at this point comes down, because voltage at this point is 15 volt minus voltage across this. So, more voltage across this, you see less voltage at this point; that means, when AC voltage is rising, that current through this is rising ,voltage at this point is decreasing; so, that is what you get it like this (Refer Slide Time: 26.34).

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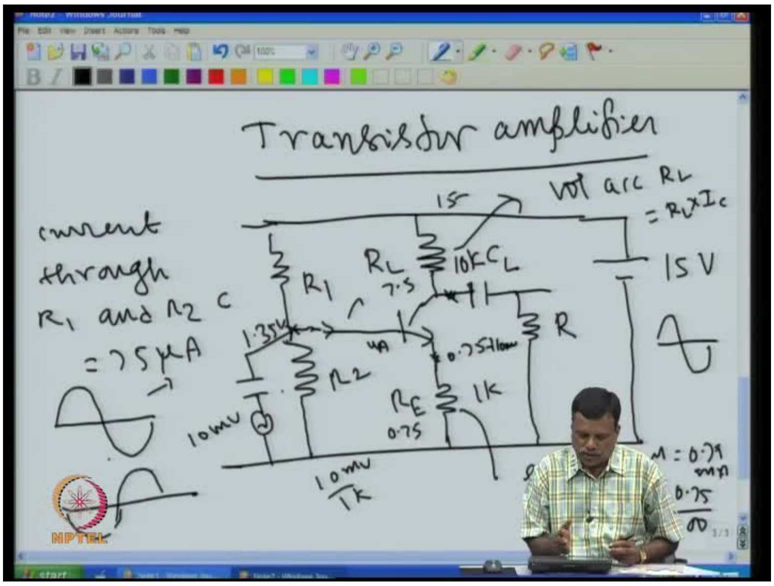

So, this is what it looks at the input and you get at the output - the inverted voltage; that is, essentially you get the input is like this, then you get the output 180 degree phase reversed comes here and of course, this amplitude is 10 times more than this (Refer Slide Time: 27.12).

Now, this AC circuit working was good and people are using this basically during the Second World War before that predominantly for radios - amplify in the radio’s signals. Radio was the main thing at that time. Before Second World War that radio usage was the main think for the electronics and everything was center around only radio. That is because, at that time, they need mainly this AC voltage to be amplified for radio use.

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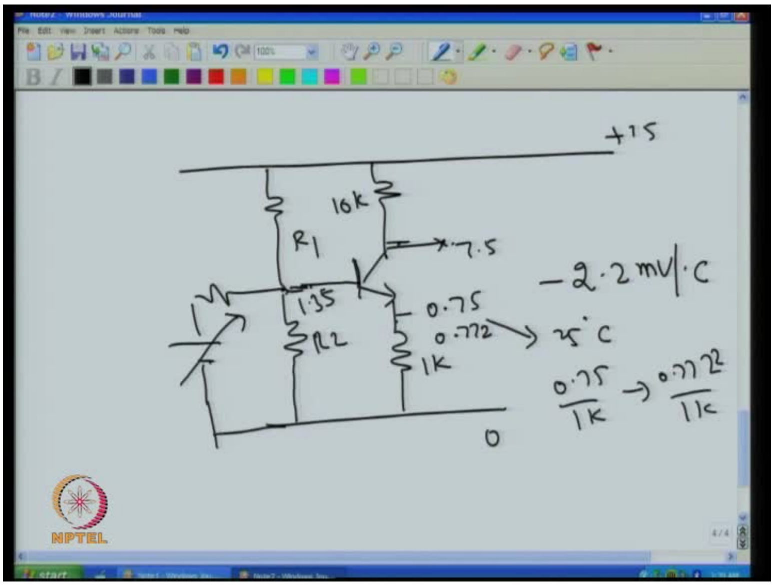

But, then when they tried to use this amplifier for DC application, then this amplifier shorted giving many problems. For example, if I try to see how to use this for DC amplification, then immediately we get into many problems. like, For example, if I have this same transistor amplifier, I want DC gain of 10; then, what I do is I will put this, I put this resistance and then apply the voltage (Refer Slide Time: 28.11), then I know that it have a gain of tens, si I put this 1k and 10 k - ratio of 10, then gains comes 10.

Then, I have to bias this, because I want to keep this one at the midpoint - 7.5, so that when the signal is applied, this will go up and down. So, I want to keep 7.5, then I know that if I put 7.5, then 7.5 volts drop should be here. Then, 0.75 volts drop here, this has to be kept at 1.35, then I can do that by selecting these resistor - this R 1 and R 2 (Refer Slide Time: 28.42). Then, if I applied DC, then I can put this and applied a DC voltage here.

Now, if this voltage if I vary, then voltage at this point will vary and voltage at this point will vary and voltage at this point will vary (Refer Slide Time: 29.05). Then, this DC voltage you will get amplified and then you will have more change than what change at you given at this base.

So, while looking at this voltage, I can say what is the voltage that is applied here, but then this looks fine from theoretical point of view. However, when there were using this they found voltage at this point was changing, even if the supply voltage was changing also. So, if the supply voltage changes, for example, if it goes to 15 to 16, then you will find originally when there no voltage was here, this was sitting at 7.5. This shown that when it goes to 16, then this voltage also will increase, then this voltage also will increase, then we will find this voltage is decreasing (Refer Slide Time: 30.01).So, with supply also, this voltage will be changing.

Similarly, other serious problem is when temperature changes, then this transistor which is kept in the ambient temperature, the temperature of this also changes. When that happens, the base-emitter voltage which was there - say the room temperature - the base emitter voltage was 0.6 for given collector current, the base emitter voltage also changes, because the temperature collection of base emitter is minus 2.2 millivolt per degree c; that is, for every 1 degree temperature rise, the base-emitter voltage decreases by 2.2 millivolt. That means, even if this supply voltage is constant, even if this base voltage is constant, for example, the temperature are 25 degree c, if the base emitter voltage is 0.6 and if this is sitting at 1.35, this you will get it as 0.75.This is the condition at 25 degree c (Refer Slide Time: 31.11).

Then, when the temperature goes up by at 10 degree, then base-emitter voltage will decrease by 22 millivolt and that will make this voltage go up by 22 millivolt. That means, this will not be 0.75, this will be 0.772; 22 millivolt will decrease and that will make this voltage to go up by 22 millivolt. That means, the current in this will increase by, in the original current was 0.75 by 1 k; now, the current had become 0.772 by 1 k. So, once this voltage increases, this current also increases, that also increases this current, then this voltage decreases (Refer Slide Time: 32.04). That means, voltage at this point changes because of this voltage change and because of this base-emitter voltage change.

Now, this is serious problem, because we are looking this point voltage at this point to reproduce what is happening here, but then voltage at this point is not dependable, because voltage at this point changes even if this changes or if the temperature changes (Refer Slide Time: 32.30). So, you are in trouble, because we are not sure whether change at occurred here is only due to this or not.

So, there are many issues like there were try to do various compensation techniques to remove this, but nevertheless the problem was, if you want amplified DC voltage, it is a problem. So, people were struggling and then mostly the applications were restricted to AC. So, transistor was not very convenient raise to amplify DC.

The same thing was there at that time vacuum tubes as well. When there were using vacuum tubes, that amplify the DC is a problem because this so called change are we call as a drift - the drift of the voltage at this point during temperature and the power supply - is a major issue.

So, various attempts were made to solve these issues. Only when these issues was solved, then the operational amplifier come in. Then, once amplifier come in and then analog electronics started going very rapidly and as well, the other digital as well as the forward power electronics also started going very rapidly after this point only. This is a very significant thing as for as electronic is concerned. If there were not solved, this DC drift problem power electronics would not have grown to this extend even today.

So, that is way, I have picked up this transistor amplifier first for AC amplification and then I had shown what is the problem for DC amplification. So, how did I solve these issues - that the drift problem and that actually was the birth of operational amplifier.

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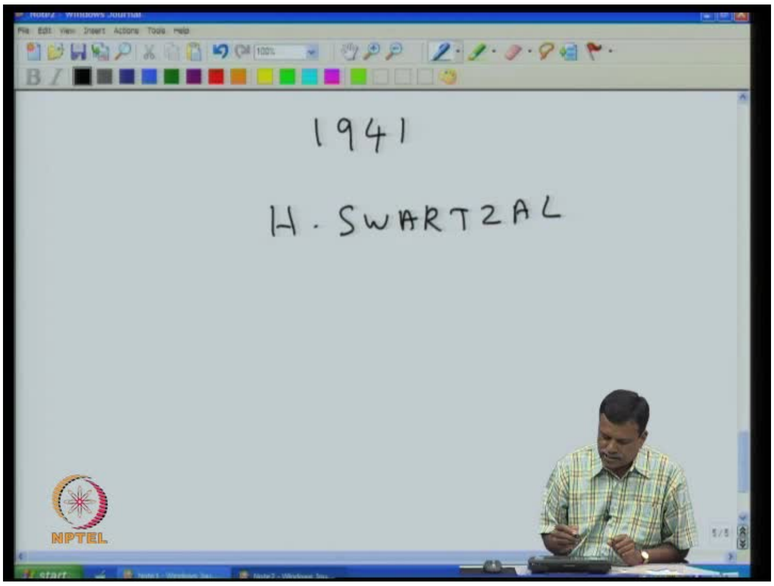

Now, actually, to see how the operational amplifier was born, we have to go back in time scale little before. Before the World War, actually the whole things were started in actually 1941. In 1941, one gentleman name H Swartzal was the one who patterned at one small circuit, which actually opened up the new topic.

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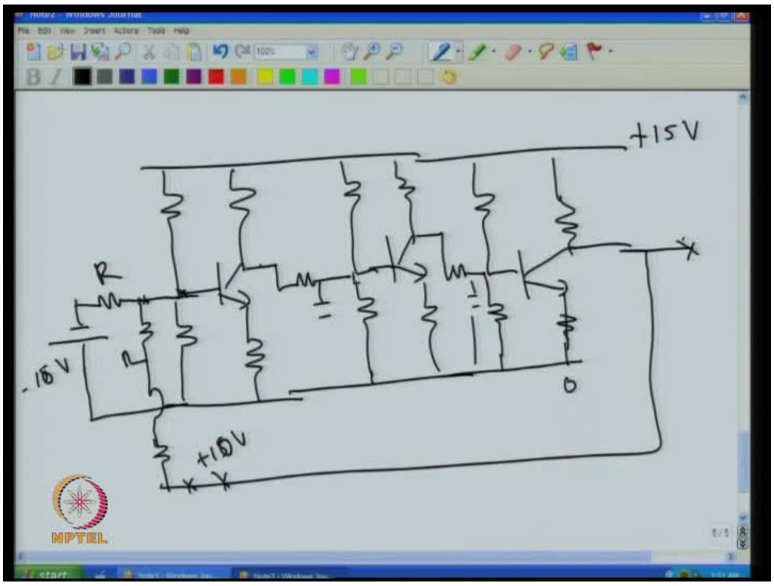

Now, if you look at the Swartzal's work, what is that he had done? Basically, what he had done was that, basically, you know, basically, here taken three same transistor amplifiers what we are discussed; he had taken three transistor amplifiers that what you are shown there; you know you have one, then the second one, then here put one more (Refer Slide Time: 36.12), basically he had taken three transistor amplifiers that what we have discuss so far. That is

Then, you are trying to applying the DC voltage and then try to get the output here. Then, this are all directly coupled here, of course, put biasing network here and then, I will not get into that right now. To explain this, what here done is basically he had connected this essentially, this then he had put in the input, for example, I connect the minus supply with respect to ground, then this input I give (Refer Slide Time: 36.51).

So, whatever voltage is here is applied to this stage, then this voltage is applied to this stage. That is, basically three stages of amplifier: first stage, second stage, this output is given to this next fellow, then this output is given to this stage and this output was given back to the first stage - he has given back to this stage (Refer Slide Time: 37.09).

So, this is given some supply voltage. In fact (( )) run it with vacuum tubes, I had shown you the transistor equivalent circuit here. So, I taken three sets of vacuum tubes and one output of the first stage output was given to second stage and second stage output was given to the third stage and third stage output was given back to the first stage.

And, this is the major development as for as the electronic is concerned and this only like to the development of operational amplifier. What here done is that, here apply the minus voltage is here, for example, if this is not there, if this is not connected, then the minus voltage would have made, this actually took conduct almost nil (Refer Slide Time: 38.04).

So, you would have got high voltage here. The high voltage here would have put low voltage here and then low voltage here would have produce the high voltage here, because once this described voltage is high, automatically you get high voltage here and that makes this one go low (Refer Slide Time: 38.23). If this is low and this voltage comes low and this one goes high.

Once this is high and suppose, if I connect this back here, if this is high, then automatically this will go high and then this will come low, then that will make it high and that will come low, but then, where it will stabilize? Because, if this increases, if this voltage increases, that force this fellow to come low. If this comes low where if this low, then this is high, low and this comes high (Refer Slide Time: 39.02). That means, if this is high, it works around and then forces this come to low. In case, if it is goes low, again this will force this one to come high.

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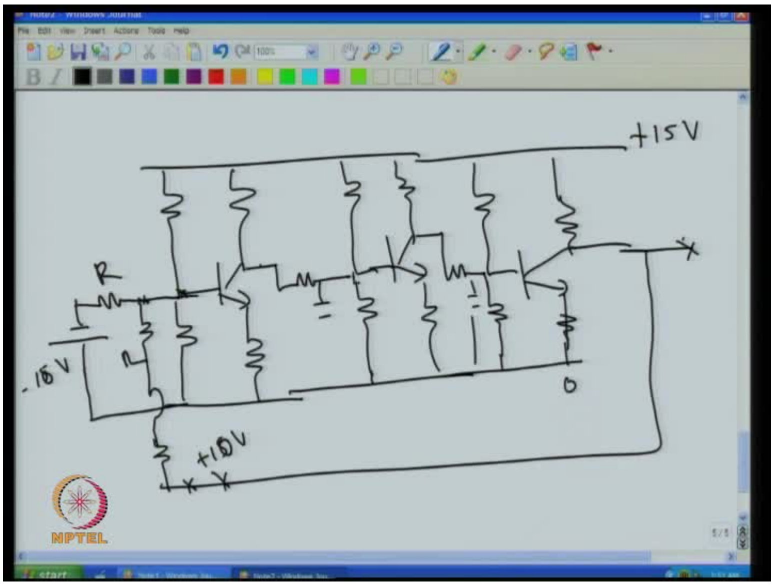

Eventually, what will happen is if I stabilize the loop by putting capacitor and so on, you eventually see this fellow which is getting contribution from this as well as from these the two contributors: one from this feedback voltage, another from this applied voltage. This fellow trying to go to 0; that is what happen because when goes to 0 or when this is just about 0.6, so it conducts and then it get some voltage, so that this also get some voltage amplified and this also get amplified voltage that it comes from here (Refer Slide Time: 39.44).

So, eventually what here shown was that if I applied 5 volt here - minus 5 volt, you will get back plus 5 volt here, so that if this resistance and this are equal, you will get almost close to 0. So, if I give minus 5, I will get plus 5; if I give minus 10, then I will get plus 10 here (Refer Slide Time: 40.05).

So, if this resistance assuming this and this are equal, then whatever voltage I am giving minus, I will get back as plus. So, if I look at this one, you are using these as output. So, if you gives minus 10, you will get plus 10 here; if you gives at this point minus 5, you will get plus 5; if gives minus 1, you will get plus 1.

That was this amplifier and we called it as summing amplifier. This we are pattern it and then this circuit become very popular; of course, at that time it was using the vacuum tubes, this was very popular. And then, they want to use this during the Second World War in the army, because during the second World War, that around 1941 british Island was attacked by Germans using aircraft everyday night actually. So, British want to develop the system by which if any aircraft enters into their space, they should hit them using electronic system.

So, radar network, radar source the incoming aircraft, but then they had gun to hit the aircrafts, but then there was no link between this radar and the gun, because if the spotted space in the radar indicating the incoming aircraft. And if there is a system which automatically connected to the gun, then the gun it automatically directed to the aircraft and if the gun fires the aircraft automatically, then there will be sure success.

But, at the time, they had this anti-aircrafts gun was there, radar was there, but then there was no electronics to link automatically these two, so that the aircraft can be hit. So, In fact, British government asked the USA to develop this system, so that when aircraft is detected by the radar, this is automatically link it to the gun. The gun automatically get directed, so that the aircraft can be hit. So, the so called gun director, that is, the gun director is nothing but electronics sets to be developed, that work was given to the USA and then it was actually given to MIT to develop this gun director.

Now, MIT looked at it and their (( )), there was with the vacuum tubes are that time they had, it was very difficult to develop. Then, this sorts paper was there and then it will look like a promising one, because it is acting like a summing amplifier - we give this plus 10 and minus 10 are summed at this point, he called it as a summing amplifier. That means, it gives a birth of analog computer. You can sum it two voltages, then the same way you can subtract or you can multiply, divide, all these functions if you perform, then you can develop a computer and unless you have a computer, you will not able to develop a gun director.

So, essentially, they want to develop analog computing machine and with using that, they want hit this aircraft. Now, we found that using this technique - this is summing amplifier - using this, if you have addition and subtraction, you can also perform multiplication and division and so on.

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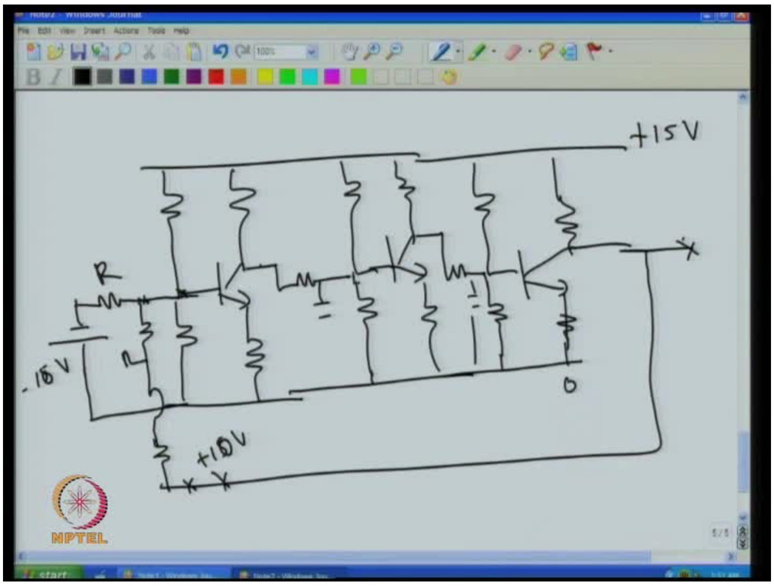

So, based on these principles, they are developed the gun director basically using this and then, in fact, they successfully connected the radar to the gun and then the spot appears in the radar. Automatically, the gun director will direct the gun to the aircraft and then the gun was fired and it supposed to go and hit the aircraft, but then when they did this one, the success rate was almost zero. The reason was it was taking an enormous time to calculate, because the coupling between these two ever oscillations, they have to put large value of capacitor at various places. And then, in fact, the gun director what MIT had developed was taking almost half an hour to spot the aircraft; to spot and direct the gun - it was taking half an hour; by the time, the aircraft had vanished.

So, German said filled, there is everyday use to bomb this one and then they were not able to develop a proper gun director; the problem was the circuit was very slow.

Then, this problem was understood and then again MIT was on the job. Then, MIT approached, MIT want to develop the new improved version of this one. So, I approached Colombia University to develop so called operational amplifier, which is I can use successfully and hit that incoming aircrafts.

So, when they approach the Colombia University, there no one develop there. Then, it was the higher head one person who supposed to develop this operational amplifier and that supposed to be used in the gun director.

Now, that I will tell the gentleman's name is still alive even today; he is alive and he said, he can develop this operational amplifier which will work in the gun director and which will be very fast in 30 days. And he developed that during that time during the World War. The so called operational amplifier that what we are seeing, he had developed that operational amplifier and that was capable of doing addition, subtraction, so called multiplication, division, differentiation, integration, all that it can do that, we know that it is called as an operational amplifier today; that is the reason that it is called as operational amplifier.

And in fact, he had developed that operational amplifier in 30 days and in fact, he had developed 300 numbers of that. And he had given it to MIT, then MIT supposed to be a computer experts, they hard wired these 300 operational amplifier to make a gun director and then, in fact, they got bell labs assistance in this.

So, put together the Columbia University, MIT and then Bell - all 3 put together, they made the first successful gun director. And that gun director was put in the next week itself in UK to detect - to hit this incoming German aircrafts.

So, when it was put into use, when German aircrafts are appeared on that day - night, that radar detected the incoming aircraft and that information automatically went to the gun director. The gun director calculated the entire position of the aircraft, the aircraft is already moving, so the gun director calculated the current position of the aircraft and then also correctly given at what direction the gun to be oriented and at what time it is fired exactly calculated, by considering the moving aircraft and then the gun was fired. That day, it was hit the aircraft 90 percentage hit rate - success rate; there is out of every hundred firing, 90 of that hit the aircrafts and the aircrafts were down.

In fact, next day, no German aircraft was seen in the sky. Actually, operational amplifier was the hero of the Second World War. In fact, it was kept as the big secret how it was developed and so on. That too, it was developed using vacuum tubes, not with transistor. Well, many of you may not be familiar todays with transistor, many of you may not be familiar with vacuum tubes; that is why, I taken the transistor equivalent of that and explain.

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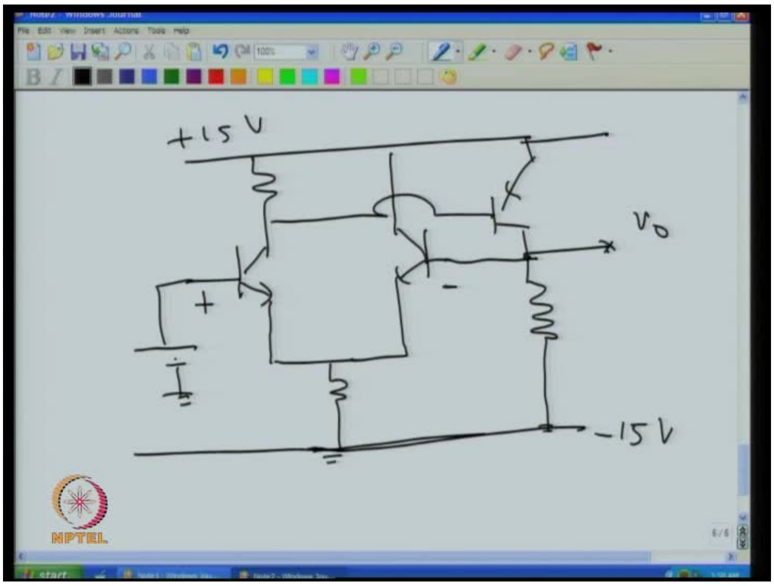

So, the story goes like that, the op amp was developed essentially to hit this aircrafts. Now, how was this operational amplifier looked at that time? If you look at the operational amplifier what they have developed during the second World War, that is for the gun director of the developed; it was just with three vacuum tubes.

If I draw the equivalent circuit of that in transistor version, that looks like this: the two vacuum tubes and then I connected this, then this is connected here and this and then the third tube was used to in this mode, equivalent of that it was run with vacuum tube, not this one and this is the output here, this the supply voltage (Refer Slide Time: 50.23). In fact, he had used plus 15, minus 15 actually the not plus, it plus 300, minus 300 volt.

So, I am showing it plus 15 and minus 15 for the transistor equivalent this output and this is the plus input of the op amp, this is the minus input of the op amp. This is the op amp equivalent that was developed during the Second World War (Refer Slide Time: 50.45).

Now, I am not telling that person’s name to keep you guessing, because he still alive and he was just 21 years old when he have developed the world’s first op amp, that we are seeing on today’s form; I will tell you in the next class what is his name. So, this is the thing that we have developed and if you see this one, the wonderful thing about it is I can use AC or DC it amplifier. For example, I give a DC voltage, then DC voltage I will voltage will be reproduced here, in this case as it is if I want amplify, I can do that.

Now, one significant thing about this is that, this output voltage will not change even if this voltage changes or even temperature changes. That is the major breakthrough because, now this operational amplifier of course it was developed only for the Second World War. But then, he has solved the main issue that if the DC voltage applied, the DC voltage was changing at that time, that problem was solved.

Now, if I look at this point, this voltage is independent of this supply voltage as well as the temperature of this transistors; it only depends upon this. That means, we can use this for amplifying the DC voltage, this can also use to amplifying the AC and also we can know that today the operational amplifier is used for integration, differentiation, multiplication, division, addition, subtraction, everything all act you can do.

So, it looks like a great magic, because the problem what we had at that time the Second World War - the output voltage changing with respect to the supply and then the temperature change was solved. And this a major breakthrough as per as electronics is concerned. Without that, probably electronics would have stop with radios, nothing else would have come. And also, you have to realize that whole computer I think the so called computer that we are seeing, there are all digital computers, but then the first computer only came only in analog.

And with that analog computer and with op amp, they had a 90 percent hit rate of the incoming air craft, that even today they cannot get it with even your Pentium 4 processor actually partly because, that today aircrafts are much more advance and so on, but nevertheless the credit should go to this hero of the Second World War.

And from then, the analog electronics as well as digital electronics and power electronics everything at grow on and this is the breaking point, but then the gentleman who is responsible for this to happen were developed this in just question of 30 days at the age of 22. He is almost forgotten and no one is remembering him and the sad story is even is not a sad story I would not tell, he had given an interview recently for the electronic design magazine is alive, that is good.

In fact, after the Second World War was over, he started his own company to make various analog instruments and he was supplying to US army his instruments. Of course, he was supplying recently even (( )) 2000 he was supplying; recently, he had sold his company also, he was mainly supplying calibration instrument, so that, you know, the equipments are kept in a perfect shape.

Probably electronics were not recognized enough; however, it is very important, understand how we able to design this, how we able to solve this drift column, that was hunting everyone at that time and that will give us good insight into the world analog electronics. And this is very important, because we will using this technique very much in this course at various places to design the electronic circuits.

So, you can go to the internet and see who is the gentleman who had developed the gun director during the Second World War, I will tell you that in the next class.

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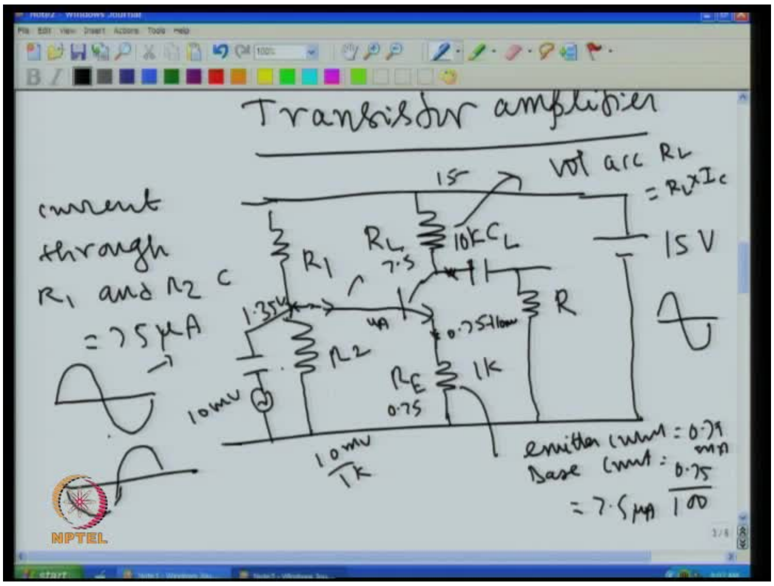

So, quickly, if you look at what we are done today, we had started our discussion with explaining what is our transistor amplifier, how the transistor amplifier works - basically the transistor whatever signal that we are giving, that is amplified with 180 degree phase difference here. And I have shown you how to select the resistances, this resistance and this resistance (Refer Slide Time: 56.55), because if I gain 10, then make sure this ratio is 10, because now this 10 k and 1 k gives me gain of 10.

I will select these two resistances, that two resistances selection depends upon what is voltage that it keep it here. If I have to fix this voltage, then I have to fix this voltage, because I know this and this referred by only 0.6.

So, to fix this resistance, first I fix voltage at this point; voltage at this point invariably fixed, at off the supply voltage; if it is 15, I will fix at it 7.5. Once this is fixed 7.5, then I know the current through this, I know the current through this, then I know the resistance value, then I will fix this voltage - that is 0.75, then this voltage is fixed (Refer Slide Time: 57.33). Once this voltage is fixed, then I will estimate the current here, then I will keep 10 times more current through this. So, you know the voltage at this point, you know the current through this, then you can select R 1 and R 2. So, that is about the transistor amplifier.

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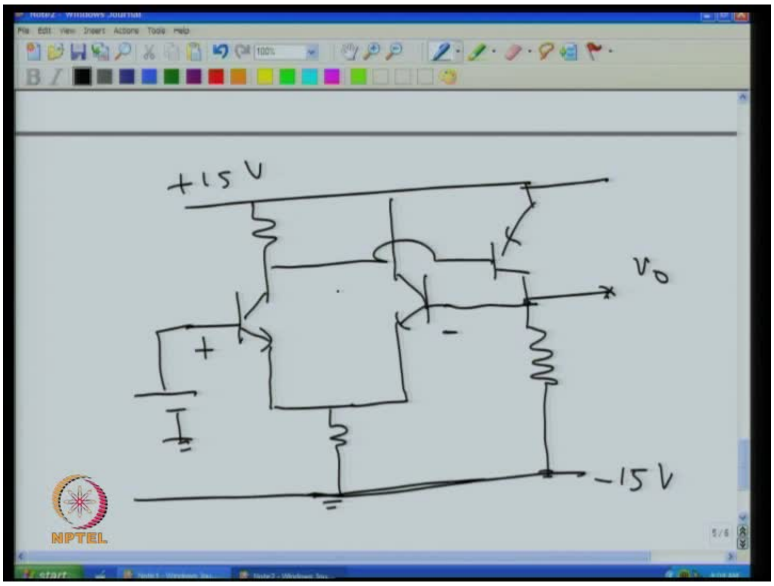

Then, the main problems was that the voltage at this point changing with respect to temperature and the supply voltage. To solve that problem only, we went to the operational amplifier, that was this circuit (Refer Slide Time: 58.02), amplifies the DC voltage here and this voltage is independent of the supply voltage and the temperature. How this happen that will see in the next class.