Electronics for Analog Signal Processing - II

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Lecture - 8
Operational Amplifier in Negative Feedback Structures (contd.)

Let us consider Example 5 which is: Design a non-inverting amplifier of gain 100. If the op amp used has open loop gain of 10 to power 5, R i of 1 mega ohm and R naught of 100 ohms; these are the typical parameters of any practical op amp; estimate the loop gain, feedback amplifier gain, input and output resistances.

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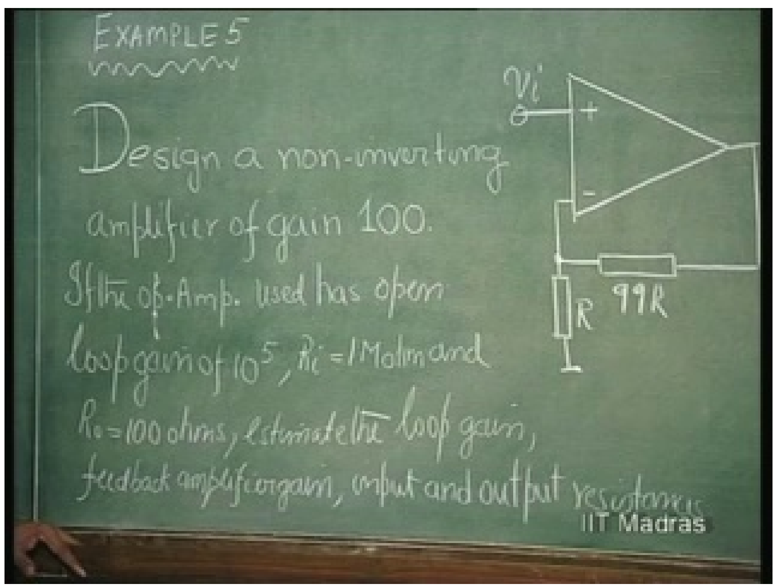

This problem illustrates the actual design involved in any amplifier using practical operational amplifier. Now you can see the circuit. It should be non-inverting amplifier. So, h feedback is given. So, gain should be 100. That means, gain is actually 1 plus R 2 over R 1 where R 1 is equal to R. This is actually R 2. So, 1 plus R 2 over R 1 is equal to 100. So, R 2 over R 1 should be equal to 99. So, R 2 over R 1 is 99. So, R 1 is taken as R; R 2 should be 99 R in order that this amplifier should give you a gain of 100.

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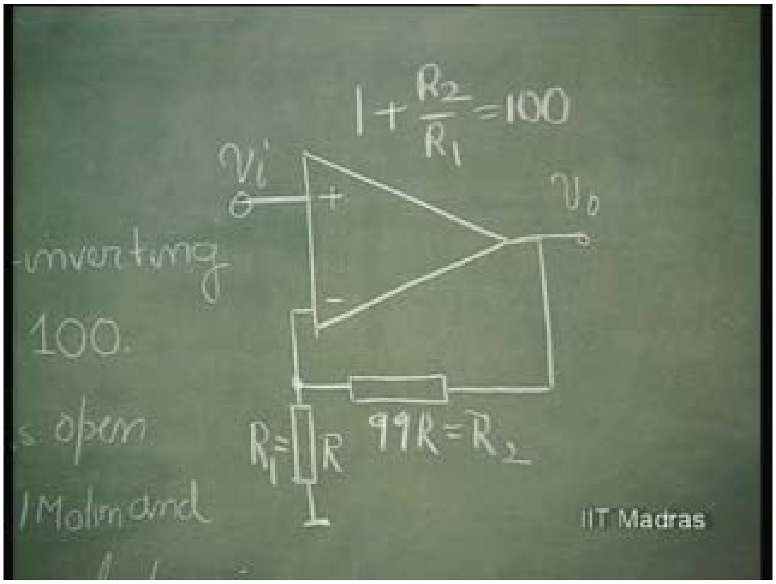

This simple design is going to work very satisfactorily in practice. Now, let us find out how much… by how much the actual gain differs from what we have designed it for, because of using a practical op amp like this. So, for that, we should once again write down the composite h parameter. Now we have become experts; and we will introduce here the resistance which is 10 to power 6 ohms, and let R be taken as 1 K.

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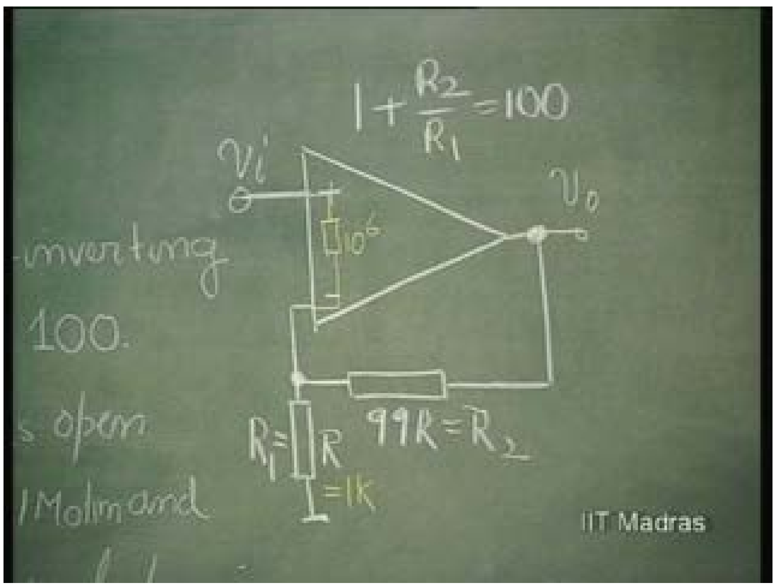

Let R be taken as 1 K. Then we will have R 2 equal to 99 K. So, R 2 plus R 1 therefore is equal to 100 K. So, this is the choice, typically.

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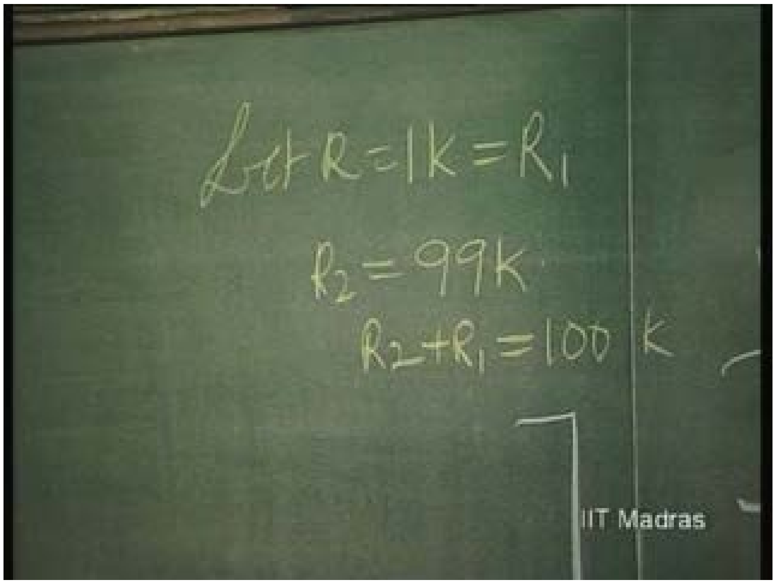

How should you select these values? Obviously, this resistance should be very small compared to R i because R i is supposed to be infinity; and this total value of resistance should be very large compared to R naught. R naught is 100 ohms. So, R 2 plus R 1 is taken as 100 Kilo ohms. So, which is quite alright and this is 1 mega ohm. Here we have R 1 coming as 1 Kilo ohm.

So, we have chosen our value such that the feedback network is acting independently of the input and output resistances of the amplifier.

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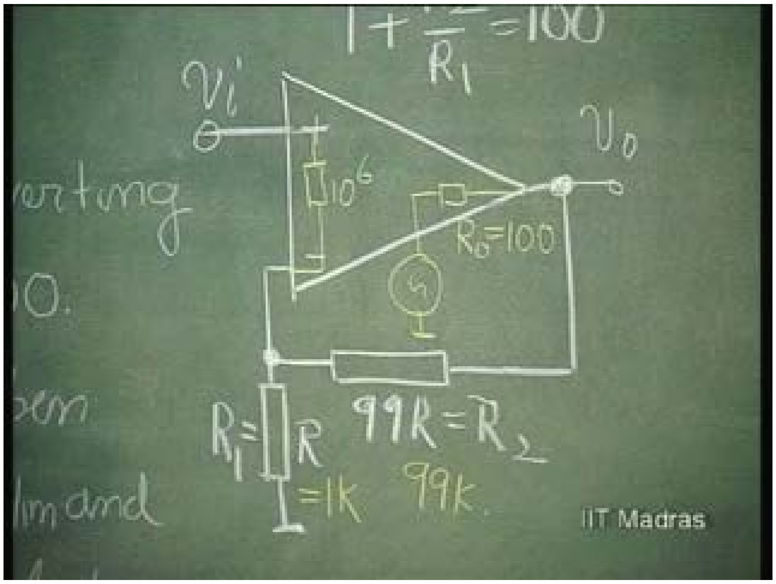

In this case therefore, h i is nothing but 10 to power 6 ohms. You short circuit this; plus 1 K parallel 99 K. 1 K parallel 99 K. 100 plus 99, sorry, 1 K plus 99. So this is, really speaking, equal to 10 to the power 6 plus point 99 K. So, this is it.

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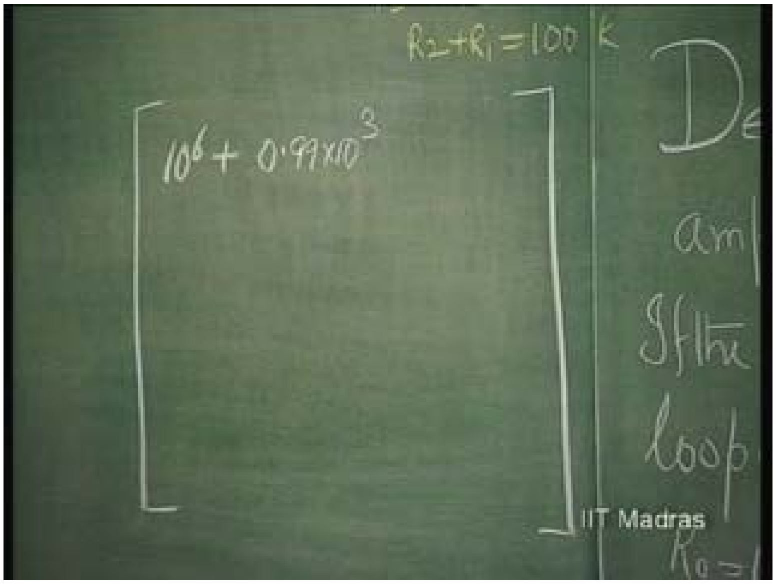

And next, V i. This… this current I i is going to develop I i into 10 to the power 6 as the voltage here. I i into 10 to the power 6.

So, this voltage V is going to be multiplied by 10 to power 6 or 10 to power, how much is it? Op amp gain? 10 to power 5 times V. So, you can see that I i into 10 to power 6 is this voltage V; that into 10 to power 5 is the gain. I i into 10 to power 6 is the input voltage V. That into 10 to power 5 is the voltage appearing there. That divided by 100 ohms is the output current. This I i divided by input current is the current gain.

So, you will get this as the output current gain. Output to input current gain, current ratio. So, the polarity of this...you can once again see here. This is plus, minus; this is positive; and the current will be going in gain. So, this is positive.

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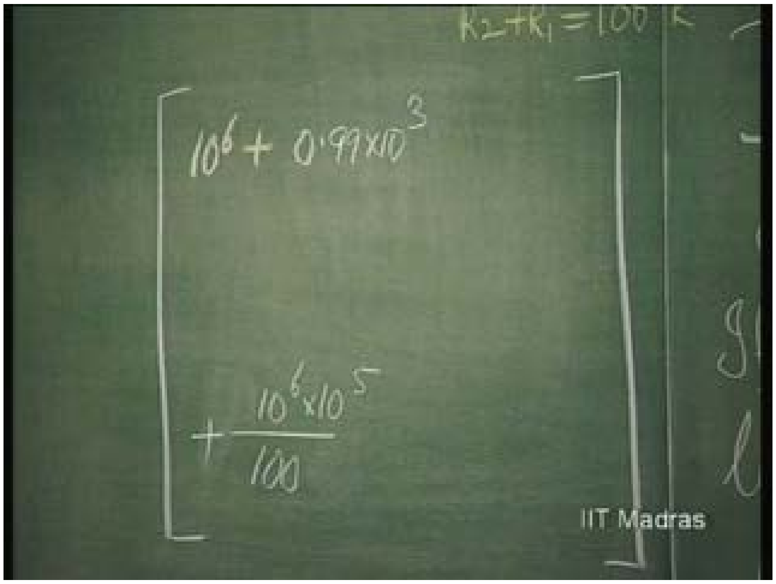

The other current gain is due to I i going there. 1 K by 1 K plus 99 K will go in the opposite direction there.

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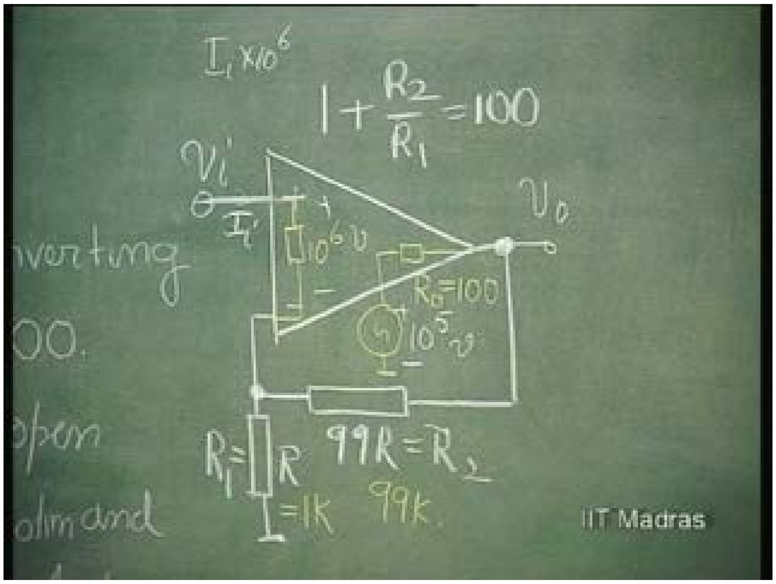

So, minus, 1 K by 1 K plus 99; 1 by 100 of this. This is going to be negligible factor. Let us just test it out here. This is plus, this is minus. I i into 10 to power six is here; and this is 10 to power 5 times this voltage V, which is I i into 10 to power 6. So, if this is… this is also going out. So, we have this also negative. This current also is going out like this current, short circuit current. So, this can be neglected. This can be neglected compared to this. So, you are straightaway neglecting it instead of carrying it over.

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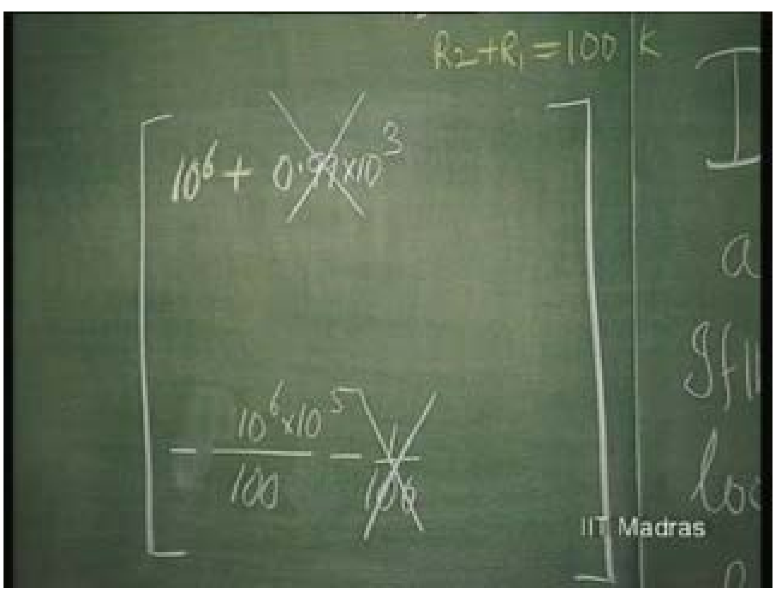

Next, the output is open circuited and apply a voltage at this point. So, feedback factor feedback factor is 1 by 1 plus 99. That is, 1 by 100. Then the output admittance is 1 by 100. Output admittance of the amplifier, plus 1 by 100 K. Once again, this can be neglected, compared to 1 by 100.

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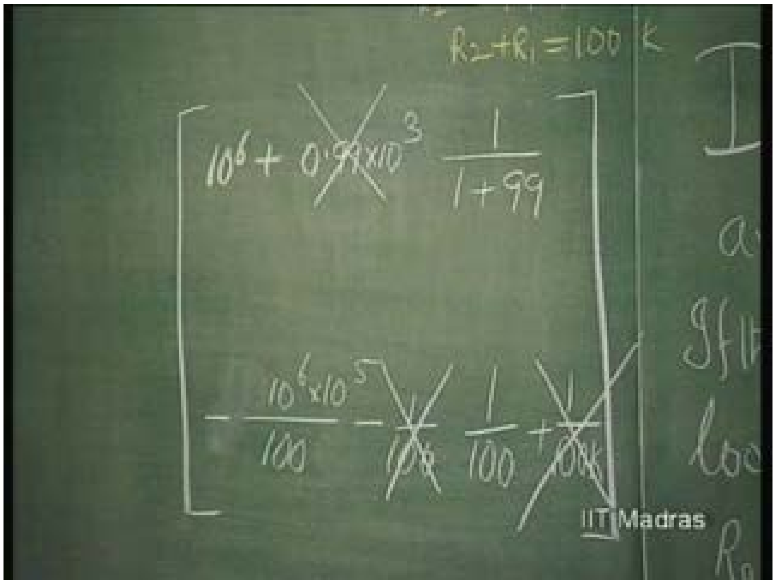

So essentially, you can see that the matrix parameter will be approximately this; 10 to power 6. This is 1 by 100. This is important. 10 to power 5, 10 to power 11 divided by 100; 10 to power 9. This is 1 by 100. So, these are the h parameters of the composite network.

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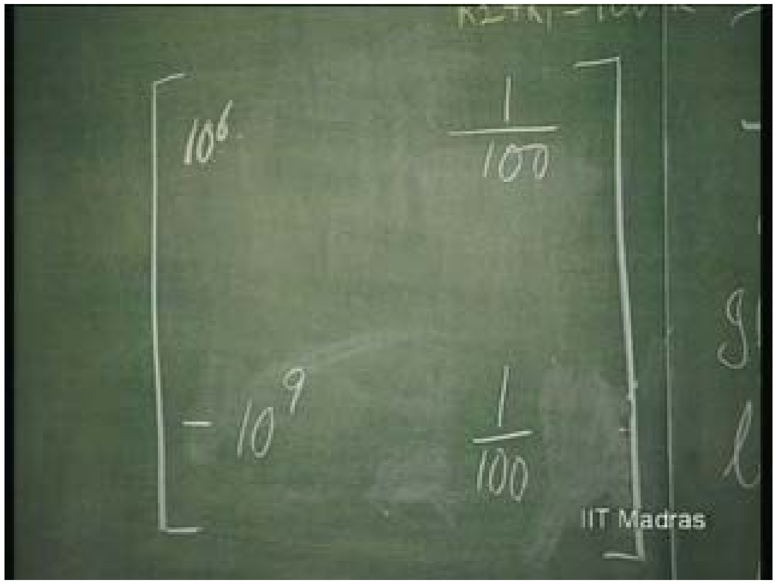

So, let us now find out Delta h. You know that this is negative feedback because this is the loop gain. Let us say, loop gain… We have been asked to find out the loop gain. This into this divided by this into this. So, 10 to power... minus, into 10 to power 9 by 100; 10 to power 7; 10 to power 6 by 100, 10 to power 4; so, 10 to power 3. 1000 is the loop gain; easily discernible here. The gain from here to here is 10 to power 5; the gain from the attenuation from here to here is 1 by 100; 10 to power 5 into 1 by 100 is 10 to power 3.

So, it is very clearly seen here because these resistances are not loading the feedback resistances. So, that is why it can be straight away seen that R i and R naught do not really affect the loop gain much. Whatever is affecting is coming as extra parameter, which is negligible.

So, Delta h is nothing but this into this. That is, 10 to power 4 plus 10 to power 7. Once again, we can neglect this compared to this. So, 10 to power 7 is Delta h.

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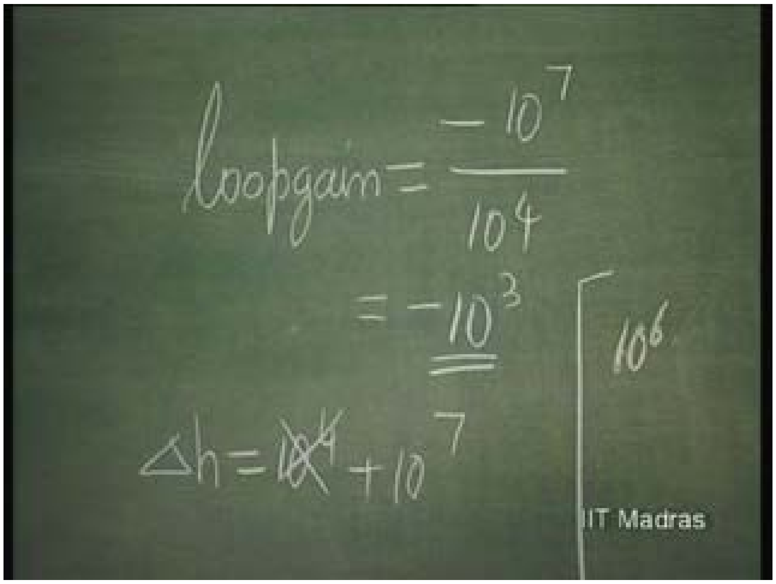

So, what is the modified g parameter here? So, I divide by Delta h throughout. So, let us first do that. Here, this is brought over here; 1 by 100 divided by Delta h.

Here, this was 10 to power 6 divided by Delta h. Here, minus this divided by Delta h; here, plus this divided by Delta h. Simple. So, the modified h parameter now becomes... What does it mean?

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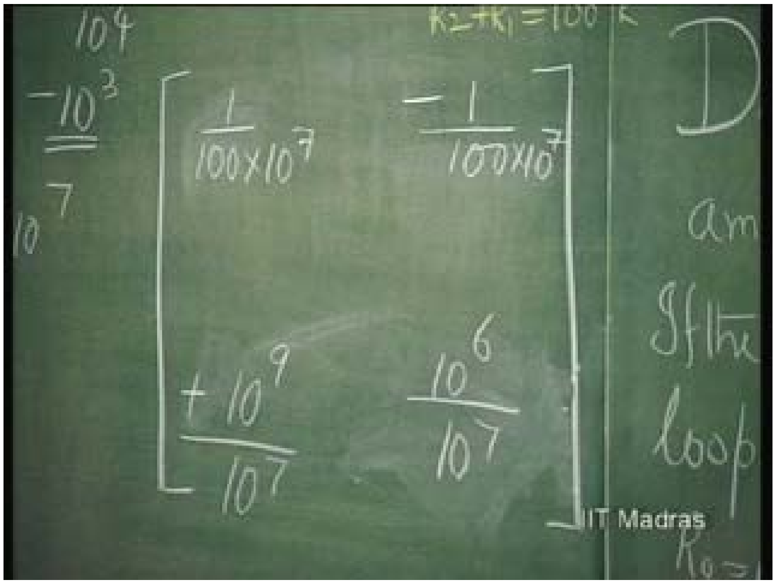

The input impedance R in of the feedback amplifier is straight away given by 1000 megaohms; original input impedance was 1 megaohm. Loop gain was 10 to power 3. So, loop... 1 plus loop gain into original impedance. That is clearly 1000 megaohm output. That is straight away given by 10 to power 6 by 10 to power 7. That is point 1 ohm. See how low output impedance has become; almost an ideal voltage source; point 1 ohm. Original output impedance was 100 ohms; that divided by 1 plus loop gain; that is 10 to power 3, is the modified thing. That is it.

So, these things can be easily evaluated. You do not have to really do these by this method. This method only tells you that certain things may become negligible compared to certain other things. Such approximations can be done here; and then we can go ahead with our usual definition for feedback modification. Everything gets modified by 1 plus loop gain.

So, the gain - that is the important factor. Voltage gain after feedback becomes very nearly equal to 100 which is... Originally, the feedback factor was 1 over 100 and inverse of the feedback factor becomes the voltage gain. So, this is the answer to this.

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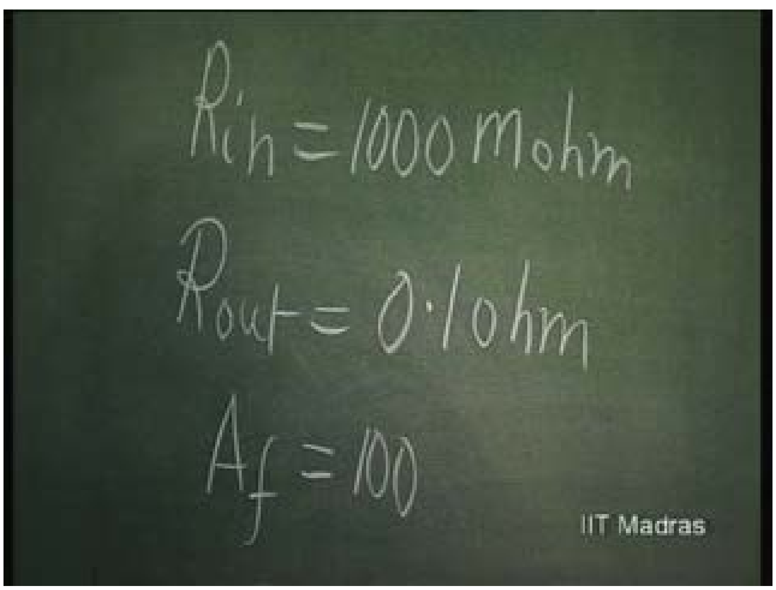

So, you can see how we can arrive at the performance of a feedback amplifier by actual evaluation of the feedback parameters, composite parameters and converting the matrix into...

from h to g. So, we will work out another problem for Y feedback so as to understand once again the approximations involved.

Next, let us design a transresistor amplifier of 10 K using operational amplifier. Transresistor amplifier with transresistor value being equal to 10 K using amplifier op amp with A naught equal to 10 to power 6, R i equal to 1 megaohm and R naught equal to 100 ohm; same op amp that we have used earlier. Determine its input and output resistances, as also the loop gain.

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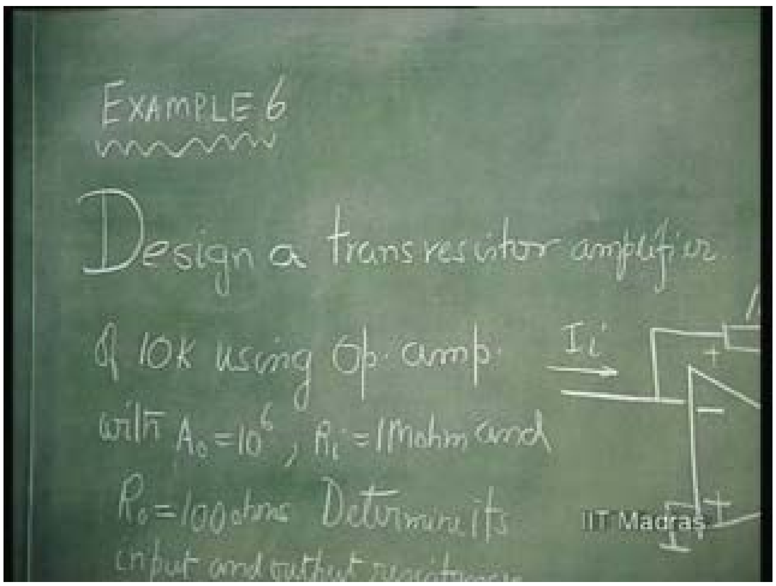

So, V naught...this is the arrangement. This is Y feedback that has to be applied in order to get a transresistor amplifier, Y feedback. So, in this case, I i will flow through entirely this 10 K. We have seen this become virtual ground and output voltage becomes minus 10 K I i. This is ideally the output.

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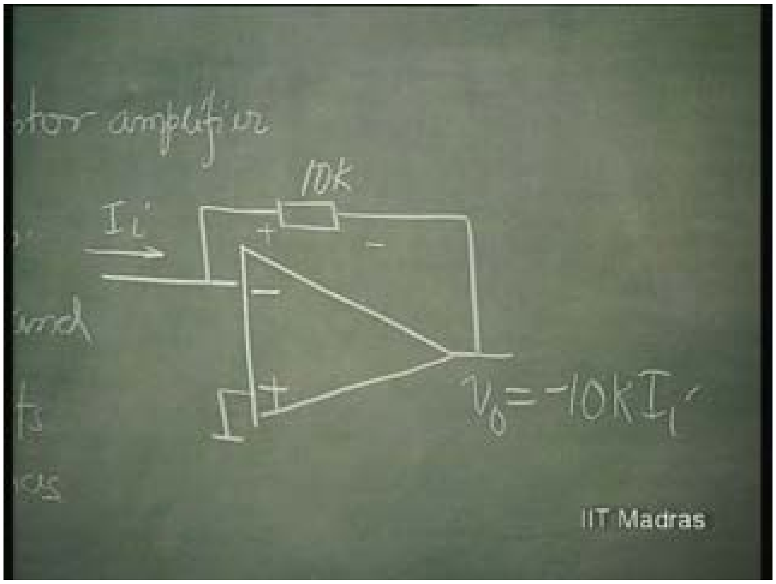

Now, because of the finite input impedance, this is 10 to power 6 and finite output impedance; that is 100 ohms and the gain here. So, that is 10 to power 5; sorry. We will give it as 10 to power 5; same as before.

So, we can now evaluate its... if this is V, the voltage here is 10 to power 5 times V. So, is it clear? Fine.

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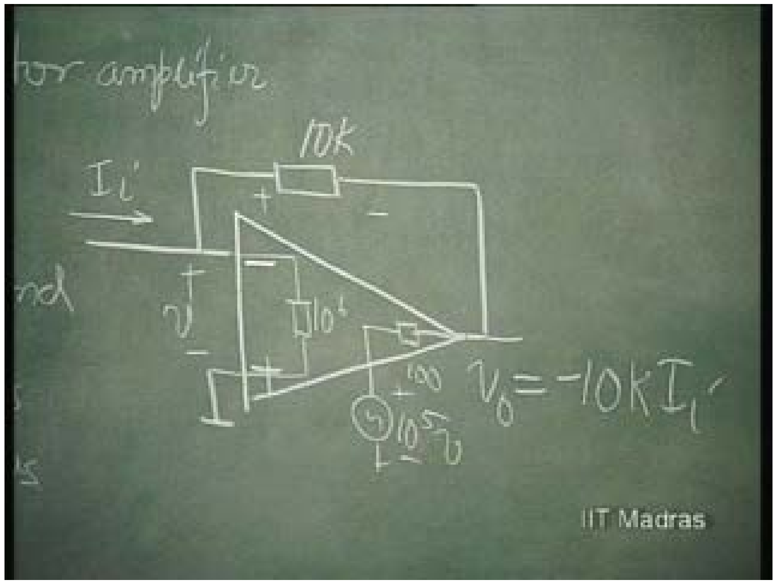

Now, this is lesser than I. This is... Once again, the parameter, composite parameter, that we have to select will be the Y parameters of the composite network which we had in the last class also determined very quickly.

So, as far as the feedback network is considered, it will give a Y parameter of 1 over 10 K at all points, at input admittance, output admittance. So, 1 over 10 K, 1 over 10 K. This is the short circuit and here minus 1 over 10 K, minus 1 over 10 K, because this is R f we said; and R f connected to an output and input will contribute 1 over R f, minus 1 over R f, minus 1 over R f and 1 over R f, as admittance parameters for the whole feedback configuration.

As for the amplifier is concerned, at the input, this one over 10 to power 6 comes into picture; at the output, this 100 ohms will be coming into picture. So, you can see that at the input this has negligible effect on this. So, this can be ignored. At the output, R f has negligible effect on this. So, this can be ignored. As far as feedback is concerned, all...may be passive network contributes; active network does not contribute.

As far as forward transfer parameter is concerned, if V i is this voltage, we have, actually speaking…this is applied to the inverting terminal. So, this will be minus plus times this voltage.

This is plus, this is minus. So, if this is V, this is minus, plus, plus, plus, minus, times 10 to power 5. So, we have the current; instead of going out, coming in. So, this is positive. So, 10 to power 5 times V divided by 100. That is the output current contribution; short circuit output current, apart from the current due to 10 K. So, you have this negligible compared to this.

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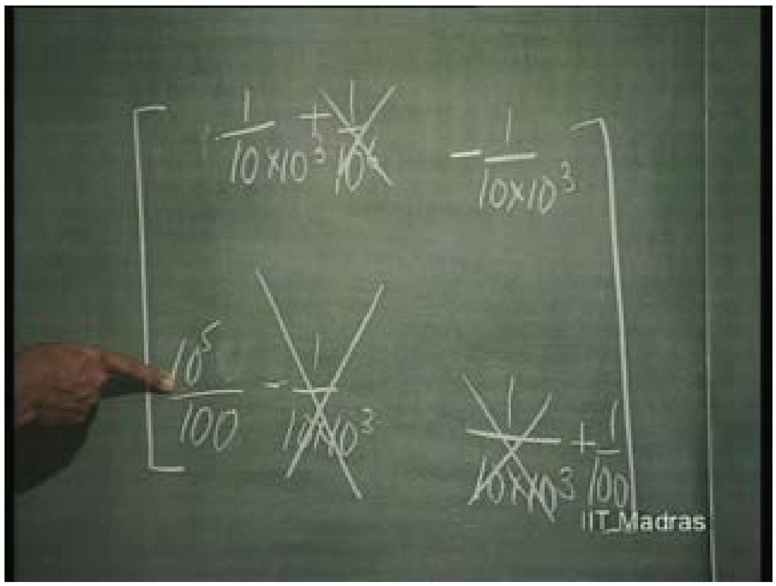

So, we will remove that what is negligible. So, this matrix really helps you in coming up with the right type of approximation for the circuit. So, the composite Y parameter just becomes this.

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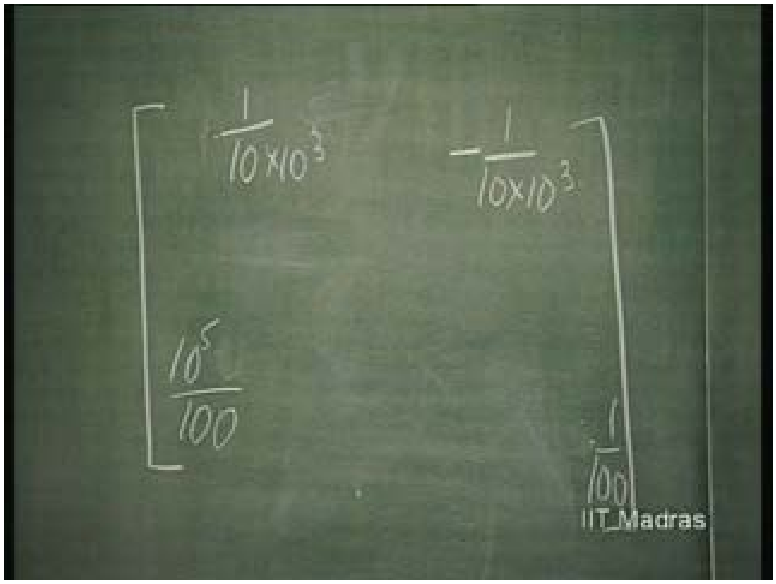

So, we can now find out the loop gain; is minus 10 to power 5 by 100, 10 to power 3; into 10 to power minus 4. 10 to power 3 into 10 to power minus 4. Here, 10 to power minus 4 into 10 to power minus 2. So, this is minus 10 to power 5, loop gain.

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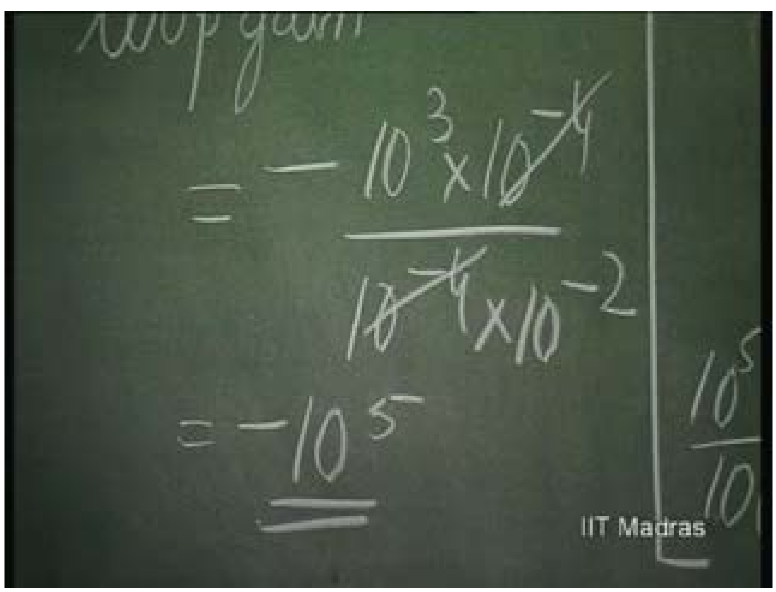

Remember, in the yesterday's class, we had done the same thing; and we got the open loop gain as the loop gain for this. This is always the case. Open loop gain is 10 to power 5 and very nearly, the open loop gain is the loop gain of this structure.

So, you can see that coming from here to here, the loop gain is 10 to power 5. This is open, very nearly open. So, loop gain is 10 to power 5. It is visible there.

So then, Delta Y is nothing but this into this; this into this plus this into this. So, this into this is 10 to power 3 into 10 to power minus 4, plus 10 to power minus 4 into 10 to power minus 2. This can be ignored in the Delta h. So, it is 10 to power minus 1. Delta Y is 10 to power minus 1.

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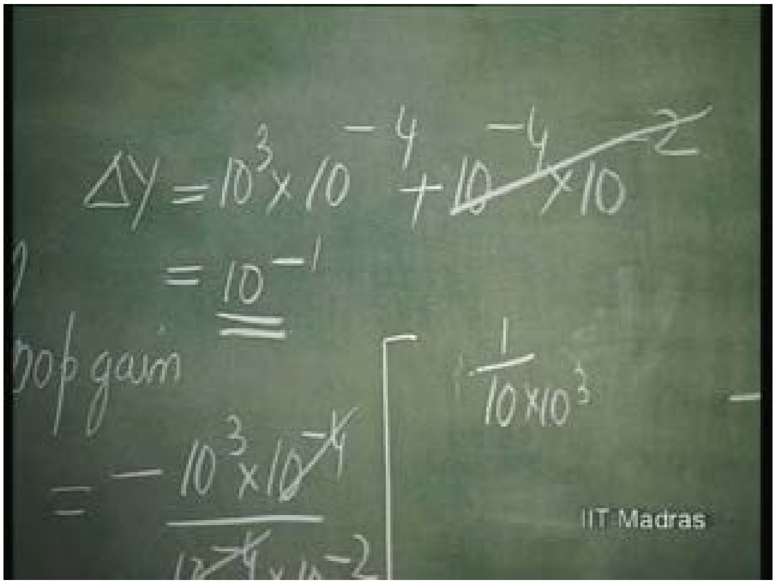

Modifying all these parameters now into Z parameter… So, we can just put 1 over 100 by 10 to power minus 1; and this one is 1 over 10 to power 4 by 10 to power minus 1. So, that becomes that. This is nothing but 1 over 10. This is nothing but 1 over 10 to power 3. So, then this becomes plus; into 10 to power minus 1. This is also 10 to power minus 1. So, that…

So, we get here 10 to power 4, as expected. What should it be? It should be nothing but, of course, this is negative. This sign I have already changed, I suppose, is positive. So, you can see here, this is nothing but Z f. That is coming out to be exactly what we wanted; and this is nothing but input impedance which is of the order of point 1 ohms; output impedance which is of the order of 10 to power minus 3 ohms.

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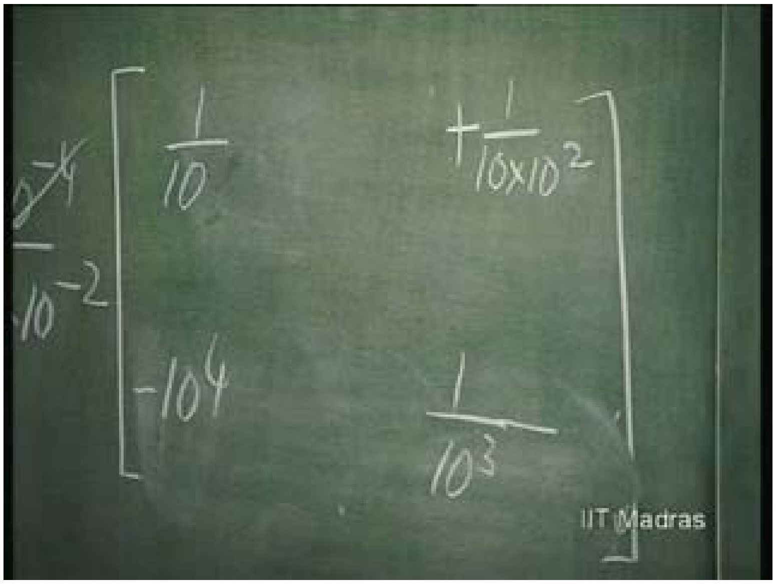

So, this is current controlled voltage source and this, we could also conclude by the loop gain. Loop gain was 10 to power 5. So, original input impedance was 10 to power 6. So, that has to be reduced by loop gain; 1 plus loop gain. So, it is going to be… What is it? 10 to power 6 divided by 10 to power 5. No. Original input impedance was actually 10 to power 6 shunted by 10 to power, this 10 K.

So, this has negligible effect. So, 10 K divided by this 10 to power 5, which is going to give you one tenth of an ohm. Original output impedance was 100 ohm shunted by, again, 10 K, which was 100 ohms divided by 10 to power 5, which is going to give you 10 to power 3; 1 over 10 to power 3 ohms.

So, you can see that all these modifications take place by the factor of 1 plus loop gain. So, we have now designed a transconductor which is a very useful element to convert current into a voltage.

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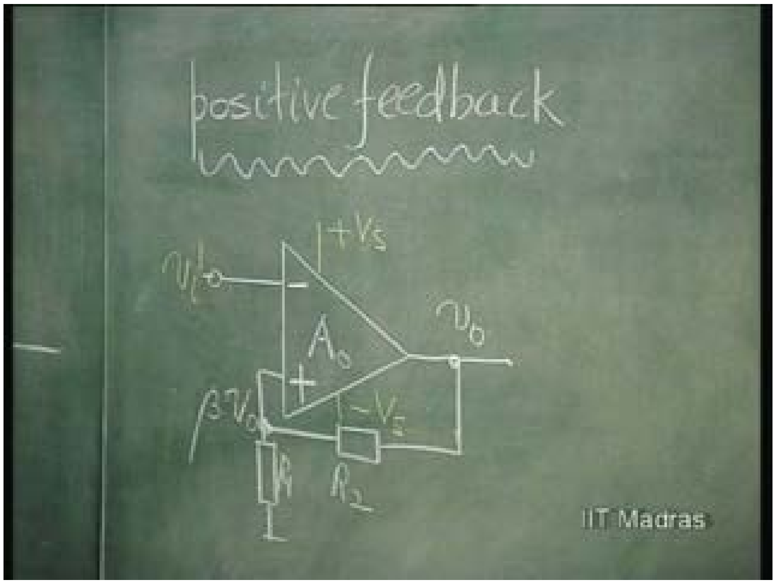

So now, consider the positive feedback configuration that we had started in the yesterday's class. Positive feedback is a situation where the loop gain is positive. That can also be depicted as a situation where the fed back voltage is aiding the input voltage and together is appearing at the actual input of the amplifier. Negative feedback is the situation where actual input is opposed by the feedback voltage and a reduced voltage appears at the input of the amplifier.

So, under this situation, we saw that the gain is going to be minus A by 1 minus A naught Beta. A naught is the D C gain independent of frequencies. So, instead of A, we will put it as A naught, now considering A naught as a number, 10 to power 5 or 10 to power 6 or something like that. So, Beta is R 1 by R 1 plus R 2; attenuation factor, this...by the passive network. So, the gain of the amplifier, V, after feedback is going to be minus A naught by 1 minus A naught Beta. This is positive feedback situation.

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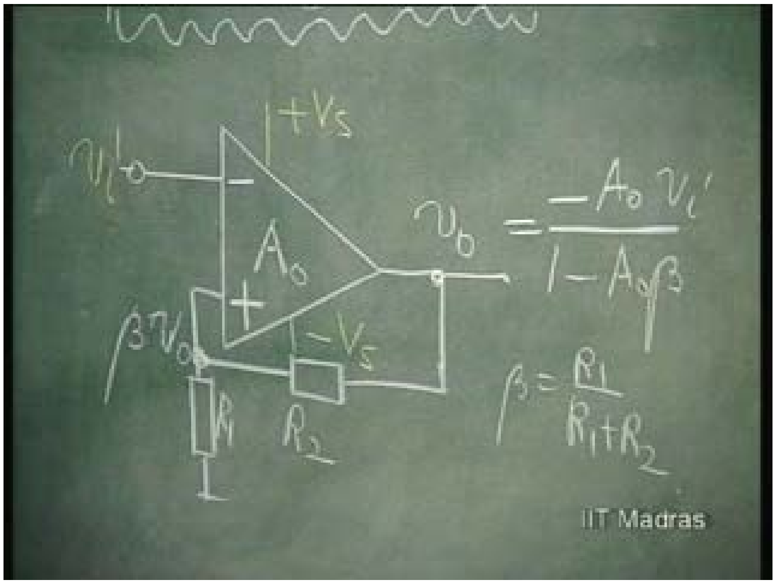

And we said, consider Beta equal to zero; there is no positive feedback. Then it is open loop. V naught is equal to minus A naught V i. That is the situation depicted here. This loop is minus A naught at the origin, where V i is zero; and please note the fact that when V i is zero, V naught is zero here. When V i is zero, V naught is zero. That is the case always with negative feedback. When V i is zero, when there is no input, output is zero.

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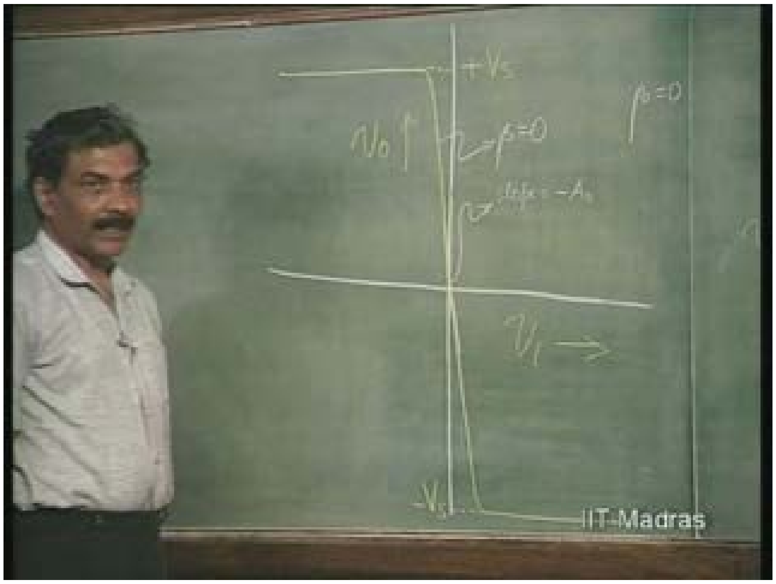

We are using plus minus power supply here so that the quiescent output voltage is zero. There is no offset. So, plus minus supply voltage is applied. Then, the saturation points will be plus V s and minus V s. So, amplifier is saturated here; it is in the active region here; is once again saturated here. So, this is the active region. With negative feedback, obviously, the gain is going to decrease. That we saw. It becomes A by 1 plus A Beta. For A Beta greater than 1, much greater than 1, it becomes 1 over Beta. So, that is a different situation.

Now we are considering the positive feedback situation. So, this is a case where it is open loop. If I give more positive feedback, then I will come into a situation something like this. This is for A Beta less than 1. That means actual gain is going to be more than the open loop gain. This slope is going to be more. Ultimately, at A Beta equal to 1, it will be exactly this. The ideal amplifier characteristics gain; gain is going to be infinity.

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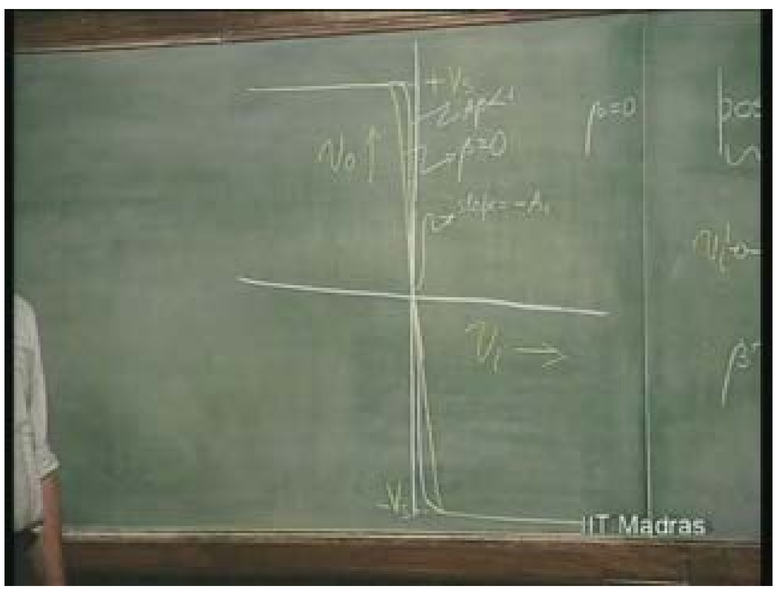

That means that is a very difficult situation. I… if gain is infinity and I multiply it by zero, I cannot say what the output is. That means output can be any voltage between plus V s and minus V s. Because it is vertical, when V i is zero, output cannot be specified because it is infinity into zero situation. Infinity is multiplied by zero. So, output can be anything between… So, that means for an input of zero, you cannot even specify the output.

So, the system is going into unstable situation. As long as V naught is multiplication of V i, you have a stable amplifier situation, even if it is minus A naught by 1 minus A naught Beta. But now, even for V i equal to zero, nothing is applied. Output is not defined. So, system has gone into unstable mode of operation; but it is very useful for other application, if you see; because, the actual gain has been made infinity here and it is... the transition region is very specific. It is suddenly transiting from plus V s to minus V s at precisely V i equal to zero.

So, you can therefore use it for what is called zero crossing detector because for a voltage which is less than zero, it is plus V s; for a voltage which is greater than zero, it is minus V s. So, it can tell you exactly when the voltage is crossing zero. So, in a situation of comparator, this positive feedback becomes useful. Otherwise, in an actual amplifier, this is never used because this is very sensitive to variation in A naught. The feedback gain is very sensitive to variation in A naught; and therefore, for positive feedback amplifiers, it is never used; but for comparators, it can be used with positive feedback.

Now, consider the situation where… this is a situation with A Beta equal to 1; this line. Now, A Beta greater than 1.

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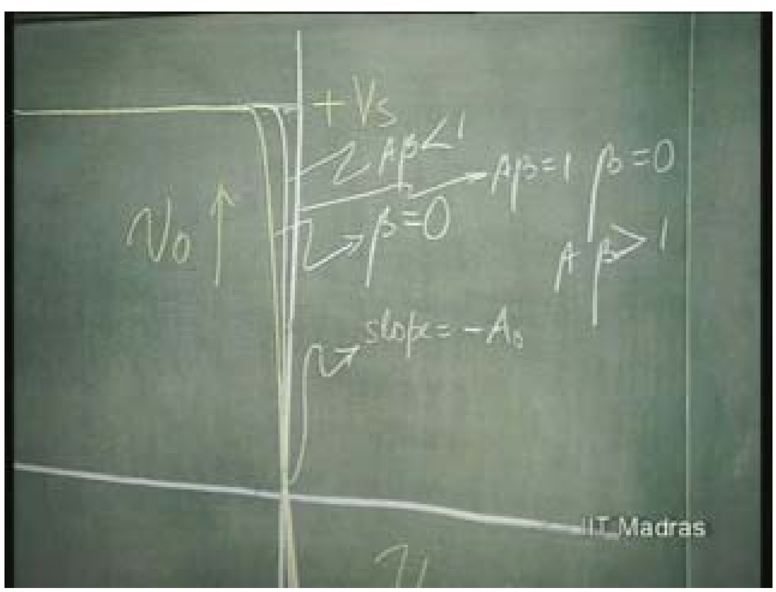

Once I say there is no correlation between output and input… output is not specified for a given input; then I cannot any longer use any equation like this. That means this equation is not valid for A naught Beta equal to 1 and greater than 1. This equation is not any longer valid. Output now is going to be… after A naught Beta, greater than 1. This is called Regenerative feedback.

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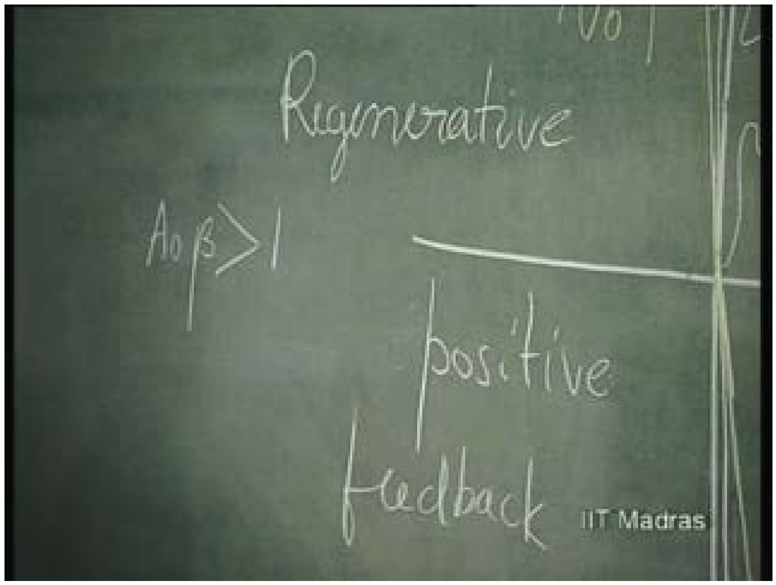

Regenerative - what does it mean? I will give an example of a situation like this. This is a flat area, let us say; and we have a person here, standing.

Now, if you push him far, he will move quite a distance. If you push him slowly with a very little force, he will move very little, depending upon his weight. That means, the movement of this person depends upon the force here and the weight here; but after the force is removed, he will remain stably in that position. So, the position of this person is stable. Why? It is dependent upon the force. If the force is considerable, he will move a considerable distance. After the force is removed, there he will be stable. So, this is a stable situation.

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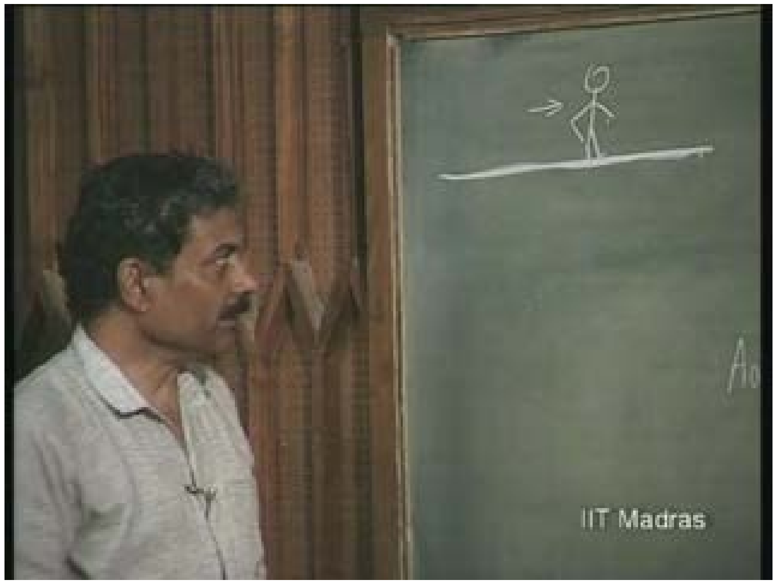

Consider… So, this person now was originally here. This is the flat surface. He has been pushed to this place or this place, somehow. Now he can balance here. No problem. He can balance here; but the least amount of disturbance, just a small impulse… it need not be kept at all; just a small impulse on him; just a push will be sufficient. Thereafter, he is going to destabilize himself on his own because if his weight is too much, he cannot balance at all thereafter. He will come down on his own by his own weight, if there is a disturbance. So, this is the stable position; this is an unstable position.

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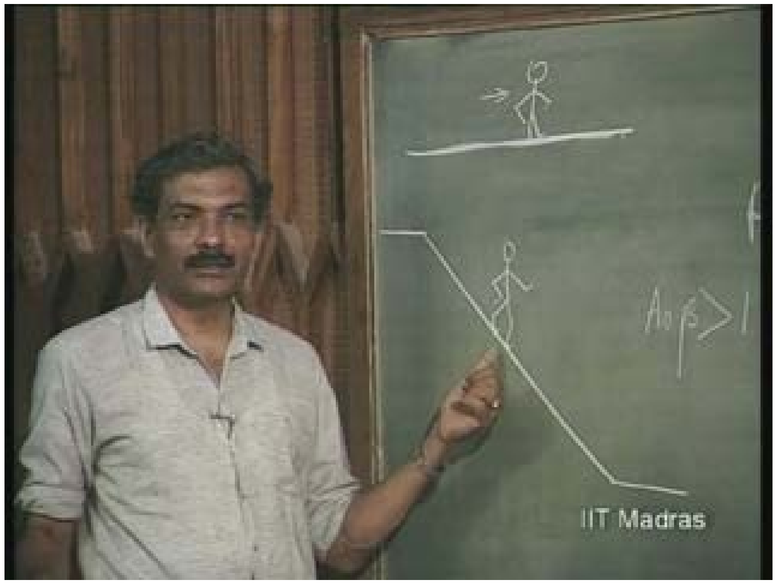

An unstable position cannot be retained by the individual for any length of time. The least amount of disturbance will take him on to a stable position here. So, this is the situation of regenerative feedback. What does it mean? Let us consider in terms of…

Let us assume that V i is zero. When V i is zero, I just told you that even if A Beta is equal to 1, output need not be zero. Output can be anything here. But, consider the situation where A Beta is greater than 1. If there is small disturbance here, that is multiplied by A naught times. That is attenuated by Beta times… since A naught into Beta is greater than 1, even that disturbance after going through the loop comes out as a higher disturbance. It is indication of… initial disturbance has been removed, tapped. After the tap, that disturbance has been removed. The movement here is generated by his own weight; and a small movement here will force him to further move. The momentum increases; so he will move down on his own.

Same thing happens here. A small disturbance, whether it is positive or negative… let us assume that it is 1 microvolt disturbance that can happen even by just switching on some power source. That 1 micro volt disturbance will be amplified by A naught and Beta appearing at that moment as a value which is greater than 1 micro volt. Here, let us say, 2 micro volts of the same polarity.

So, 2 micro volts will get further amplified. So, it will go on moving in the same direction and ultimately it will go to the maximum possible here. That is the saturation. So, if I have started with positive 1 micro volt, it will go to positive saturation; if I started with negative micro volt, it will go to the negative saturation.

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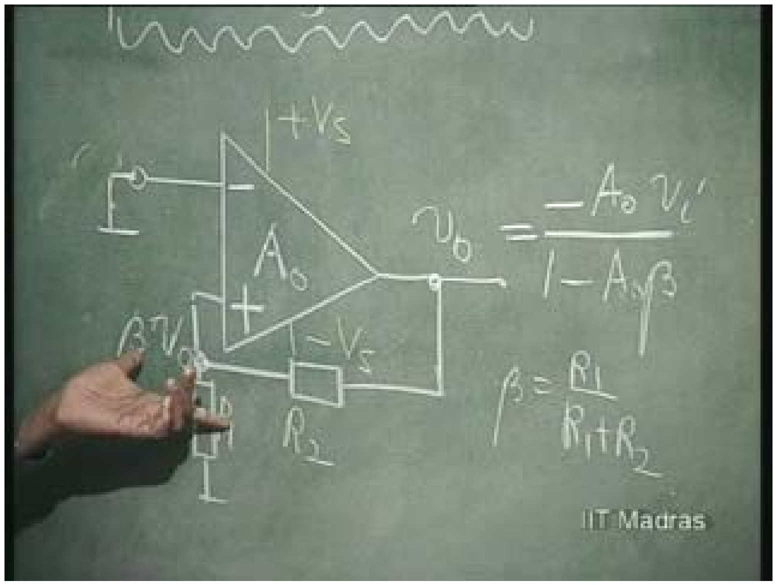

I cannot therefore say, if V i is zero, at what point output is going to be. It could be either minus V s or plus V s; that much I am sure of. It cannot be any voltage between plus V s and minus V s. As long as it is in the active region, it is moving, always. So, the the moment this amplifier is brought into the active region, that is this region, there, it is equivalent to coming to a slope. It will then come to either plus V s or minus V s both of which are the stable states of this amplifier. So, this is called regenerative feedback.

If A Beta is less than 1, you will see that this, all these points, fed back voltages, should be simultaneously existing; which means, A Beta less than 1, the series which is 1 plus A Beta plus A Beta square, etcetera, will become a stable output. As long as the input is there, output will be stable at a certain value. The moment input is removed, output will go off.

So, that is why, in the case of ordinary positive feedback where A Beta is less than 1, output is stable; whereas, in the case of positive feedback which is regenerative, which is A Beta greater than 1, the disturbance itself is causing disturbance in the same direction, which is more, such as to further move it in a direction ultimately leading towards a stable state, which is either plus V s or minus V s, depending upon the initial disturbance.

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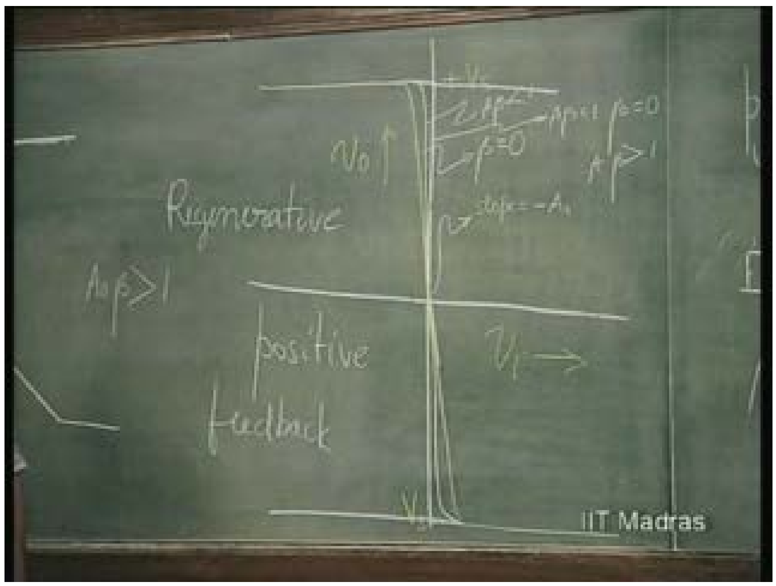

So, this is the case. Let us consider that A Beta is very much greater than 1 but it is regenerative positive feedback. Now, we will discuss it in this manner. What I am saying is, as long as V i is zero, output of such a regenerative feedback network can only be in two states: either plus V s or minus V s, in the case of positive feedback with A Beta less than 1, or negative feedback output is equal to zero, when input is zero.

This is the difference between regenerative feedback and positive feedback which is non-regenerative and negative feedback. Is it clear? Now, that circuit, the circuit with positive feedback is popularly known as regenerative feedback; is known as, what is that? - Schmitt trigger; a very important circuit, particularly in digital domain; because it has no place in analog domain; because output is either high or low, whatever be the input. And such a circuit is very suitable for an interface situation. This is called Schmitt trigger.

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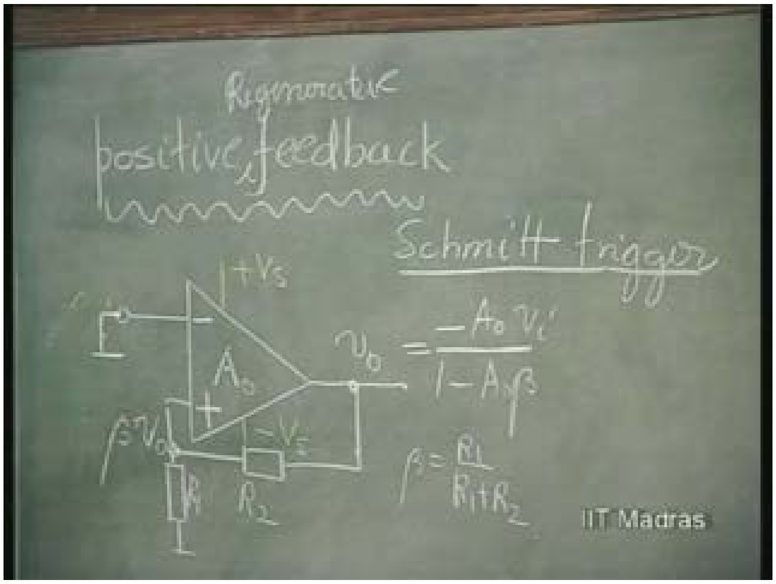

So, as circuit with positive regenerative feedback is popularly known as Schmitt trigger… I mean, please understand why it is called trigger. The disturbance can be generated by applying a small voltage disturbance or current disturbance such as to make it go into the active region. Thereafter, it will always go on its own, without further change in voltage, from one stable state to the other stable state. That is why it is called Schmitt trigger, so the disturbance is appearing as a trigger.

Now, let us understand this better. Regenerative feedback. As I told you, output of this… as long as A Beta is greater than 1… now, we have concluded... For V i large negative, let us consider. V i large negative. Output has to be positive saturation. For V i large negative, output has to be positive saturation, V s. So, this is plus V s; for V i large negative, output is at plus V s.

If this is at plus V s, this will be at what? Beta V s. Now, when will this enter active region? When V i comes close to Beta V s. Then only it will enter the active region. We have told that if A naught is very high, it will enter active region only when this voltage becomes very close to this voltage. So, this will go into regenerative feedback mode the moment V i comes close to Beta V s. Until that time, output will be at plus V s.

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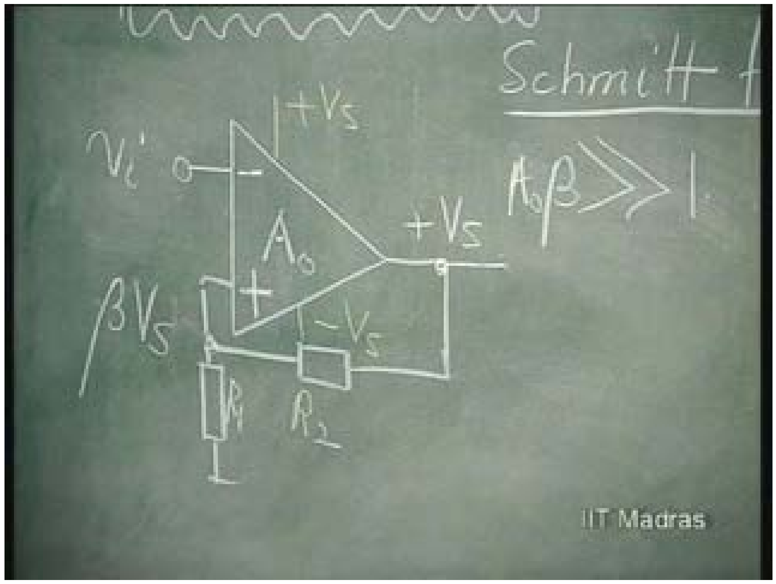

So, this is going into regenerative feedback mode and thereafter it will go to what? - the least amount of disturbance will take it from plus V s to minus V s.

This is a very important phenomena. Just see. The regenerative feedback comes into action only when this voltage comes close to this voltage. Thereafter, it changes state from plus V s to minus V s. This goes to…from Beta V s to minus Beta V s. So, this voltage has changed to minus Beta V s. Now, if this voltage decreases, it will not change state at plus Beta V s; the voltage with which it is compared is minus Beta V s.

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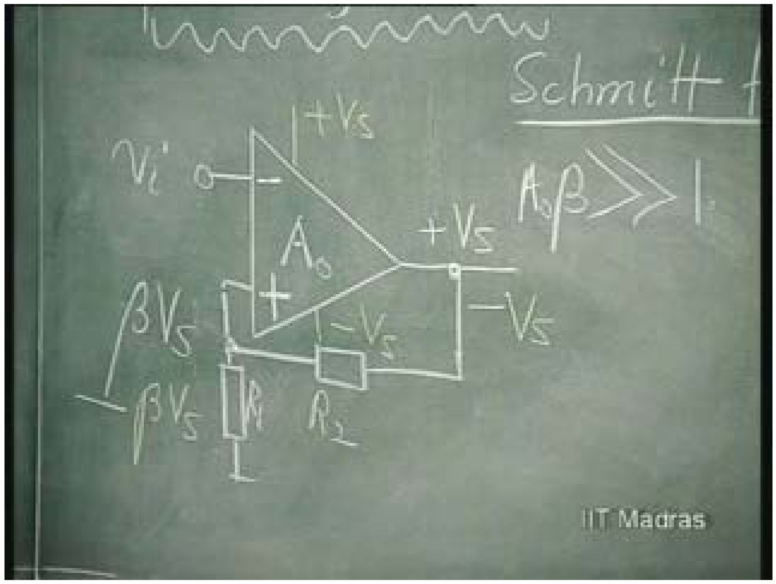

So, it will go on like this. Go on like this and will change state only at what? - minus Beta V s. So, this is what is called hysteresis.

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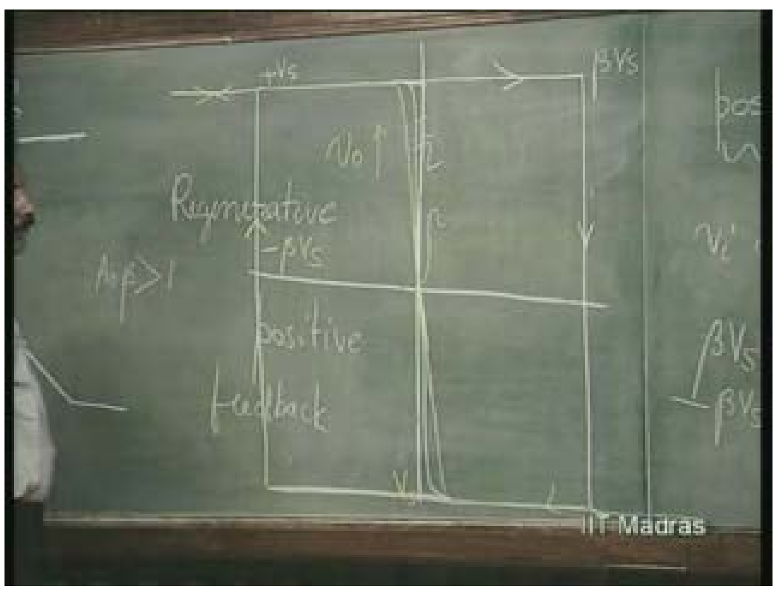

The circuit has memory. The circuit has memory. Why is it our amplifier circuit does not have memory? It is…output depends upon the instant of magnitude of voltage at that instant of time appearing at the input.

Here, output depends upon whether the input is increasing or input is decreasing; because, if the input is increasing, it says, I will change state only at Beta V s. If the input is decreasing, it says, I will change state only at minus Beta V s. So, if it is increasing or decreasing, what does it mean? It has memory because how does it know whether it is increasing or decreasing? Only if it knows its previous state compared to present state, it will know whether it is increasing or decreasing. That is why it has memory.

So, this is an important circuit block; semiconductor memory, it is also called. After the advent of this, things got revolutionized. You can think of… you could think of a computer in a chip only because of the existence of semiconductor memory. Prior to that, such a characteristic was being exhibited by what is called magnetic core. So, this was very complicated because for memory, you used to use magnetic core and for other processes you use active devices like transistors.

The moment we had this made available, we could store information here. So, we have a very important circuit element; that is, Schmitt trigger. This characteristic is called the hysteresis; and the extent of hysteresis depends upon Beta, A Beta. So, if A Beta is made much greater than 1, then specifically, if you actually join this loop which has no physical meaning, this has no physical meaning, this slope is going to be 1 over Beta, obviously.

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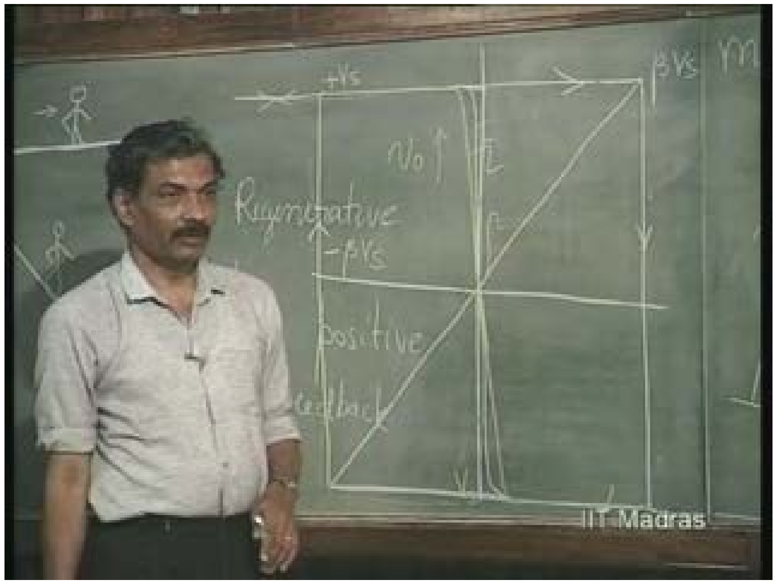

So, in fact, that expression, you see, minus A naught divided by 1 minus A naught should not be used; but if A naught Beta is much greater than 1, it is becoming 1 over Beta. It just indicates… if we join these corner points, this slope is 1 over Beta; corner points of transition from one state to the other state. This particular circuit has innumerous applications in digital circuits for wave shaping.

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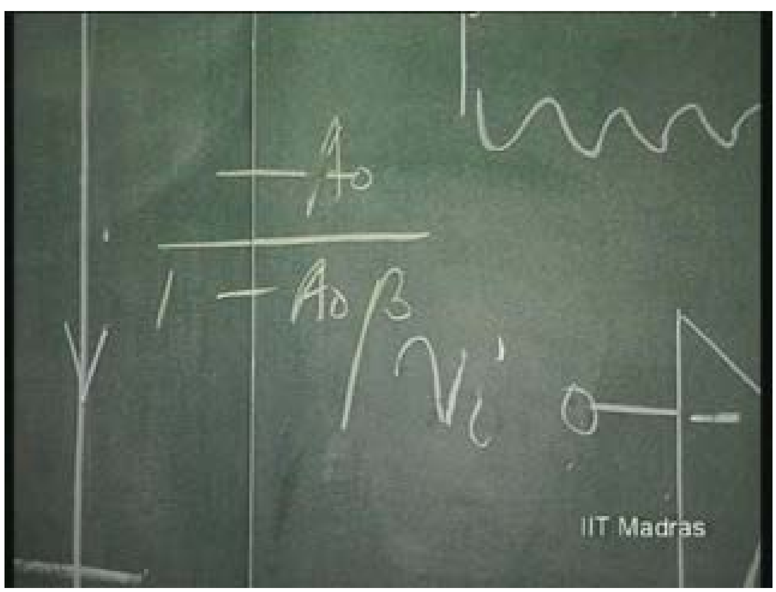

That… you have data transmitted in terms of ones and zeroes. So, this data, when it is transmitted through the cable, gets distorted because of the distributed effect of capacitors, etcetera; and gets attenuated, etcetera; and therefore gets distorted, and you want to reshape it so that the transitions of the pulses become very sharp.

So, converting the pulses which are out of shape into pulses which can become ones with sharp edges…this Schmitt trigger is always used. So, this is the entry point into a circuit. All the data transmitted pulses should come through a Schmitt trigger before they are processed further in any circuit. Otherwise, triggering becomes virtually impossible. So, this is a circuit which is very commonly used in digital circuits; in analog circuits, in the sense, we can use this also for square wave generator, etcetera.

We will see the application of this in the next class.