Analog ICs
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Lecture - 14
Switched Mode Regulator and Operational Amplifiers (Four basic types)

In the last class we were discussing the switched mode regulator. We understood about the DC to DC converter. We saw that V_0 is equal to V_i tau by T. We said that by varying tau by T which is called duty cycle we can maintain V_0 constant when V_i is changing. This kind of thing is done by using this information of control. That is, I am sampling V_0 and comparing it with V_{ref}.

Just as I do in the normal voltage regulator I sample V_0, how do I sample V_0?
I take V_0 and take R_1 by R_1 plus R_2 by V_0 and compare it with V_{ref}. And that was fed to a comparator earlier which was actually acting as an amplifier to control the base current of the pass transistor so that the pass transistor voltage drop is getting adjusted depending upon the error here. At that time the pass transistor was working in the active region.

Now, once again sampling V_0 R_1 by R_1 plus R_2 comparing it with again a V_{ref} giving it to a comparator but this comparator makes sure that the transistor is never going to continuously operate in active region but will be always in the mode of switch. The transistor should be acting as a switch. So, we have to make sure that it acts as a switch. That is done by giving what is called regenerative positive feedback to the comparator and the comparator is nothing but a symmetric trigger. So it makes sure that it always operates either in high or low so as to drive the transistor switch either to off state or to completely on state or saturation state. This is what is done by using this piece of information.

Now how do I actually change the tau by T?
That means now I make sure that the duty cycle for which the transistor is going to conduct is going to be controlled by this information which is the output sampled voltage and reference. This difference is now going to control the duty cycle. So it is a voltage controlled duty cycle generator that is required for this. A DC voltage controlled duty cycle generator. In communication terminology this circuit is called a pulse width modulator.

Now this pulse modulator scheme is very important in making the stage work in what is called class démodé. The transistor is always going to work either in saturation or in cutoff. So this kind of operation is called class D operation. And this principle is used in designing power amplifiers, in designing controller circuits here and also in communication for modulating the width by means of signal.

A variety of applications are there for this information. It is also used in multipliers, tau by T if it can be voltage controlled then it becomes nothing but a multiplier. We will see all these things when we discuss about IC multipliers later. But for the time being it is enough if you know that this principle is one of the most important principles in controls, communications and all these areas.

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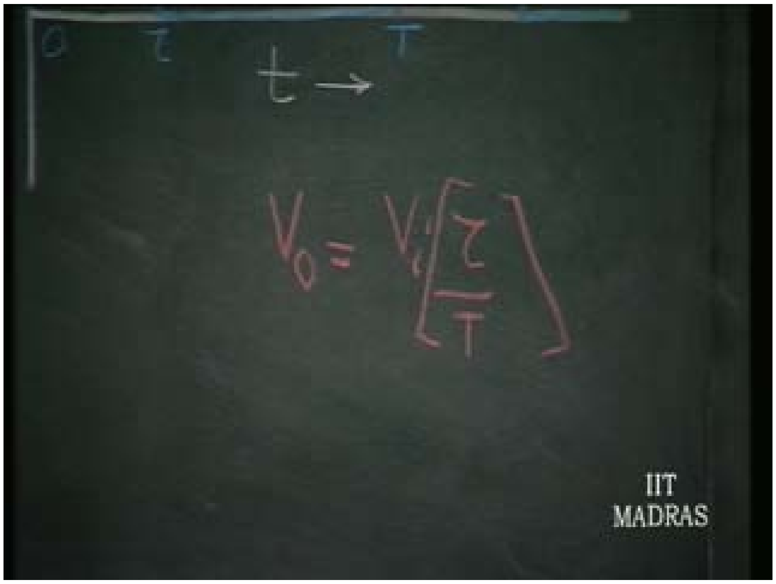

So V_i into tau by T is going to be maintained constant by the switch mode regulator. We will see the converter basics further. Yesterday we discussed all about the waveforms after making certain approximations. This is the input waveform.

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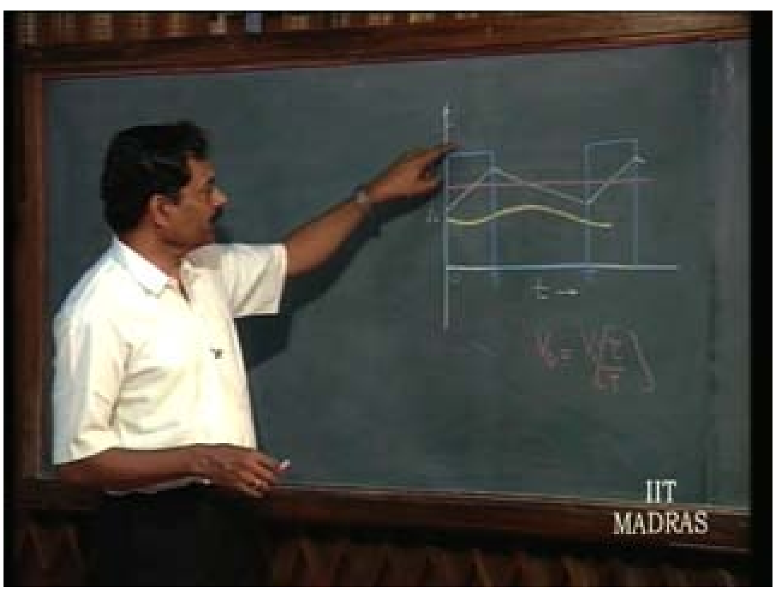

After it is switched it is going to V_i and 0 that is made sure by this. These are complementary switches. Now there is no need for control switch like this here.

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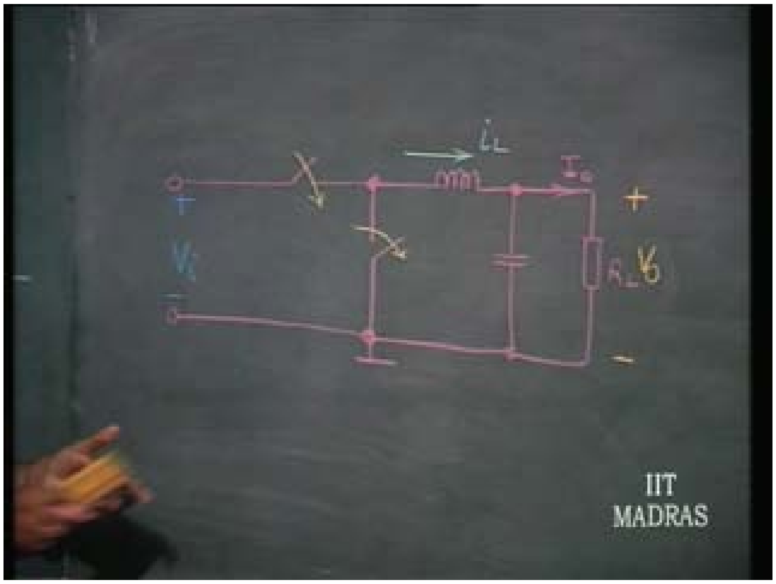

This operation can be done simply by a diode which is again a switch but it is a two terminal switch. It is switching on by making it get forward biased. How do I make it get forward biased? It is by pumping in the current in the forward direction it gets forward biased, this is important. It is biased by means of a current. By pumping in a current in this direction it gets forward biased. And at that time voltage across it is 0. Then by applying a voltage in the reverse biased direction it is open circuited. So this is the way a diode can operate as a switch.

By applying a voltage in the reverse direction it is switched off and by applying a current in the forward direction it is switched on. So this is made sure because when V_i is applied the V_i voltage is appearing directly across the diode and diode is off. So, when this is connected V_i is across the diode and it is reverse biasing the diode and the diode makes sure that this portion of the thing is off.

Next, when this is open the current in the inductor cannot change suddenly so it continues to flow but since the current has to be sustained the current is going to bias the diode in the forward direction so the diode is getting on automatically and the voltage across it is sustained to be 0. Automatically this is 0 and this is V0 and therefore the current starts decreasing in this direction. So over this period as long as V_i is not connected the current is going on decreasing linearly and suddenly again the switch is on the diode is off immediately and the current is going to increase. This is what we saw in the last class except that we have changed the switch now. Otherwise the same thing can be done by using complementary switches here which gets for example q here as its input and q bar here.

Hence, q and q bar has the gate input of the Fet switches here, that is also possible. But using only one control switch and a diode the same thing can be done. So the entire converter has the following components now. A switch is obviously a transistor switch and a diode is a power diode because it has to carry the load current anyway. Again the inductor also has to be designed to carry the load current and a capacitor rated for that voltage whatever it is. These are the things that are necessary. One important point in the design of this is, the inductor has to be wound with thick wire because you want to make the resistance as small as possible.

Simultaneously we have to also permit the load current to flow through the inductor. This is one part of the design. And the capacitor has to be a good capacitor. You might say the leakage resistance is going to be a part of the load, no, there should be low series resistance associated with the capacitor. We have assumed under our discussion of ripple that the entire voltage this voltage flows through the capacitor and the capacitor has been taken as ideal capacitor where the voltage across the capacitor is 1 by c integral idt that is only when it is ideal. If there is a series resistance the ripple will be totally because of this current flowing through the series resistance.

So if you find the ripple of the output is higher than what you have estimated by this approximation which is 1 by 8 times delta i_L into T times by c, peak to peak ripple. So, this is the peak to peak ripple if the resistance through this is assumed to be series with this is assumed to be 0. Otherwise the triangular waveform is going to cause a drop across it depending upon the value of the [….. 13:27] this delta I into R. This is quite often the mistake that is committed you will be surprised to see if you are using a bad capacitor that the ripple is more than what you have estimated using this. You are now capable of designing a good converter.

Now we would like to see how to generate the control circuit for this?
Therefore I would take from this the same combination of resistance we used for the series pass regulator we are using R_1 and R_2 sample the output so we get beta times V_0 here so this is going to be compared using a comparator with V_{ref}. I would like to know whether the duty cycle has to be increased. If the input voltage is increased duty cycle has to be decreased. If the input voltage is decreased duty cycle has to be increased. So, that information is obtained by finding out what this voltage is. I want the output to be maintained constant. So beta times V_0 is compared with V reference such that duty cycle of this switch whatever is maintained constant.

Obviously this switch is a transistor switch and now what else has to come into picture. This voltage has to generate a pulse train whose duty cycle is controlled by this voltage. That can be done by using a triangular waveform and another comparator.

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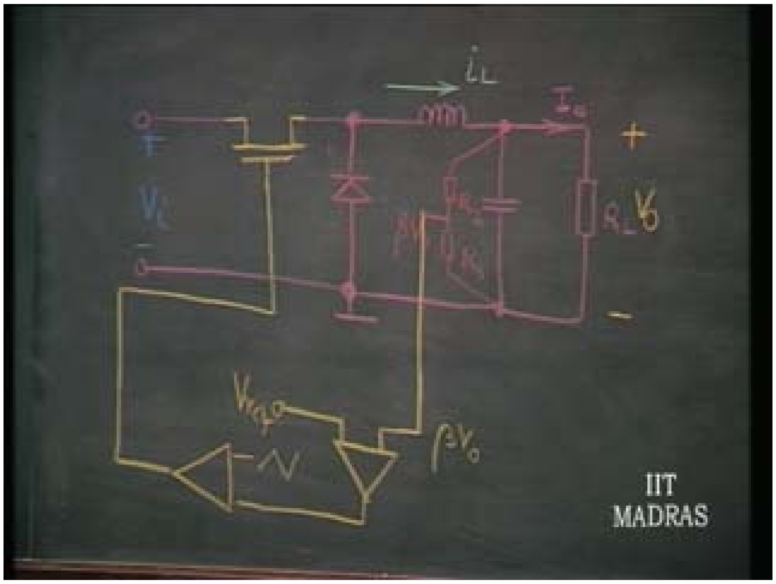

We are having a triangular waveform, let us suppose. Now, if a triangular waveform with peak voltage equal to V_p and time period equal to t is applied to a comparator whose other voltage the input voltage being connected to ground, let us consider this as plus and this as minus, so now what will be the output? It is going to be a square wave.

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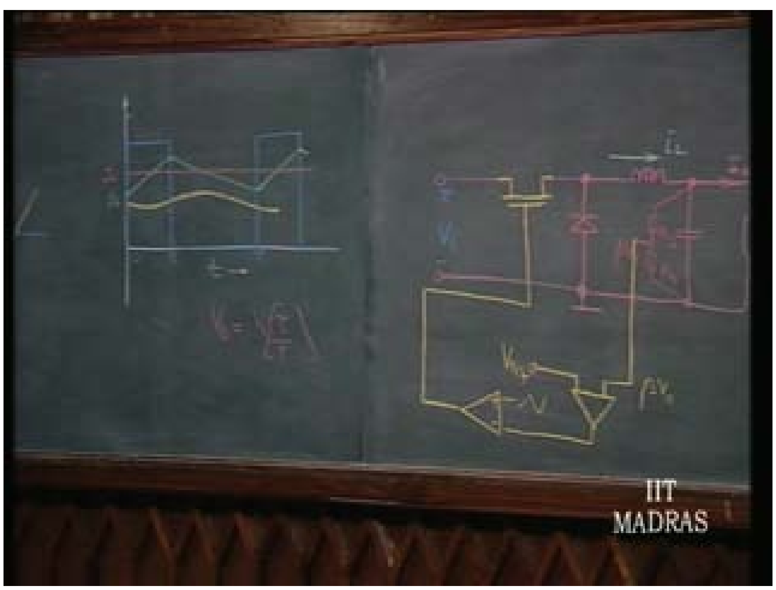

If this is connected to ground and you apply a triangular wave then the output is going to be a square wave. So, if this voltage with which it is compared is not 0 but something finite, if it is this, then it is going to high state during this period and it will go to low state during this period.

Now this is the supply voltage. So this is the duty cycle, let us suppose tau so this will be T minus tau. If I vary this it will now generate an output pulse whose width is controlled by this voltage. This is nothing but a simple pulse width modulator, linear in the sense, the width is going to be linearly related to the control voltage here. This is the control voltage, this is V_p so this is V_c. Using similar triangles here V_p is the height of this triangle V_p minus V_c which is nothing but T by 2 by tau.

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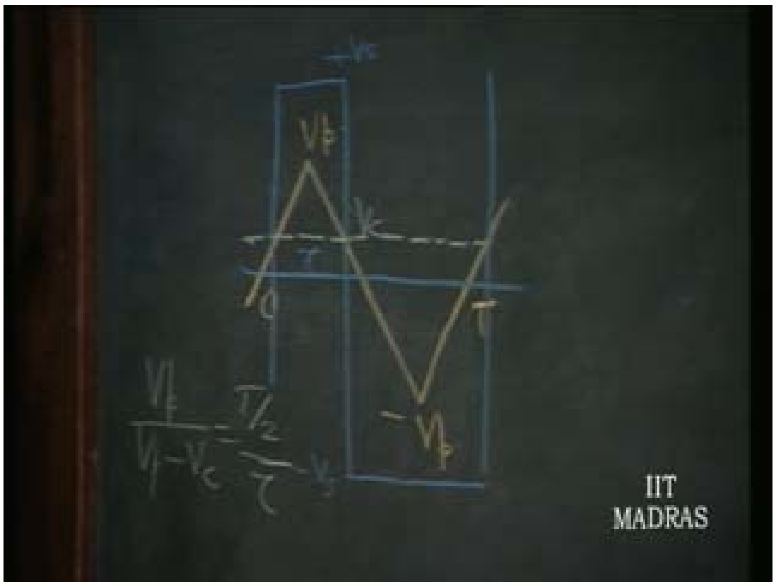

Now we can get some information about how tau by T is going to vary. The tau by T from this is nothing but, tau by T is equal to ½ into 1 minus V_c by V_p. You can see a very simple idea for modulation using a simple comparator that the duty cycle of this circuit is directly proportional to the control voltage. We are now discussing a situation of pulse width modulator and not relevant to this, so if this control voltage is audio then you have an output pulse width train whose width is modulated by the audio and if this is applied to a power switch properly it can be connected to a load which is having a pulse train whose width is controlled by the audio. Now if it is connected to the load through a filter you will get the audio output.

That means efficiency of that power amplifier is going to be theoretically hundred percent. That power amplifier is called class d amplifier. In this particular regulator case this information is used for control purposes and not for other purposes. So the control voltage V_c here is going to modulate this train of pulses occurring at a frequency is equal to 1 by T in a suitable manner so that this voltage is same as this voltage. Therefore the output voltage will so adjust itself, this is like in the case of any negative feedback operational amplifier circuit, as far as this whole mode of operation is concerned you can say that there is some DC coming here and the effect of DC is to maintain this DC voltage equal to 0 like in any operational amplifier structure. The feedback from here to this should be purely negative feedback.

So, from here to this there is going to be a negative feedback situation such that this voltage here is going to be controlled so that the switches are operating in either on or off mode never in active region. This is made sure by this kind of operation. This is one of the most popular schemes for switched mode regulator. Of course there are other schemes where it is self regenerative. That means if you give regenerative feedback it itself can oscillate, the whole scheme of this structure can oscillate.

Whereas here the frequency input is coming from external source. That means I have to have a source here which can generate a triangular wave of desired frequency. So here the design frequency is known to you. If it is made regenerative feedback structure and this itself is made an oscillator then we have to adopt complicated analysis procedure for finding out the frequency of oscillation. So this oscillation frequency is externally controlled pulse width modulated voltage switched mode regulator.

Therefore most of these circuits L, C diode and even the switches have to be provided externally because these are going to be the power components. Rest of the components namely the control circuitry and the pulse generator etc can be put internally. So you will get these pulse width modulators, circuits as ICs. The whole scheme will be available to you as a single chip IC suitable for switched mode power supply application including the voltage reference with 0 temperature coefficient etc.

Therefore ultimately we have been able to obtain a switched mode power supply whose output voltage can be maintained constant irrespective of the volt variation in V_i. I wanted to bring this idea of false width modulation which is an important idea repeatedly used in IC applications in a variety of control communications.

Now we are coming to one of the most important building blocks of analog VLSI namely the operational amplifier.

Operational amplifier: As the name itself implies is used for operational purposes. The operation we are meaning here are the mathematical operations that is why it got the name operational amplifier. The mathematical operation of, here linear operations are what are talked of, so it is the addition, subtraction, integration and differentiation. These are the four basic linear operations which are very much in usage in analog signal processing. That is what is meant by operational and for that purpose we have to have an active device block and the most important device block which was readily amenable for such integration was operational amplifier. It required the help of large number of active components to be put together so as to get high open loop gain.

The nature of this business operation comes about because of high open loop gain but this is an old concept. Hence, now we will call it as high open loop transfer parameter. It need not be gain it can be voltage gain, current gain, transresistance or transconductance resulting in four types of operational amplifiers all of which can be used for the mathematical purpose of addition, subtraction, integration and differentiation. It is historical accident that whenever we mean operational amplifier we took it for granted that it is operational voltage amplifier.

These days because of the ease of fabrication and functional utility of the circuit over a wide range of frequencies other operational amplifiers or becoming more prominent than operational voltage amplifier which was the first amplifier integrated or made available in large numbers and this became a basic building block for most of the analog signal processing systems. It is important that obviously we understand how this particular operational amplifier got evolved in the whole process of design.

Now, for the time being we will first consider operational voltage amplifiers. Strictly speaking if it is an ideal control source what is it going to be called? It is going to be VCVS Voltage Controlled Voltage Source which can only be expressed by one parameter that is VCVS. We have discussed this in the feedback, that is, in order to get VCVS we have to obtain give h feedback but the resulting parameter which is going to be very near to the ideal parameter is the g parameter. So this is going to be g_{21} and this is 0, this is 0 and this is 0.

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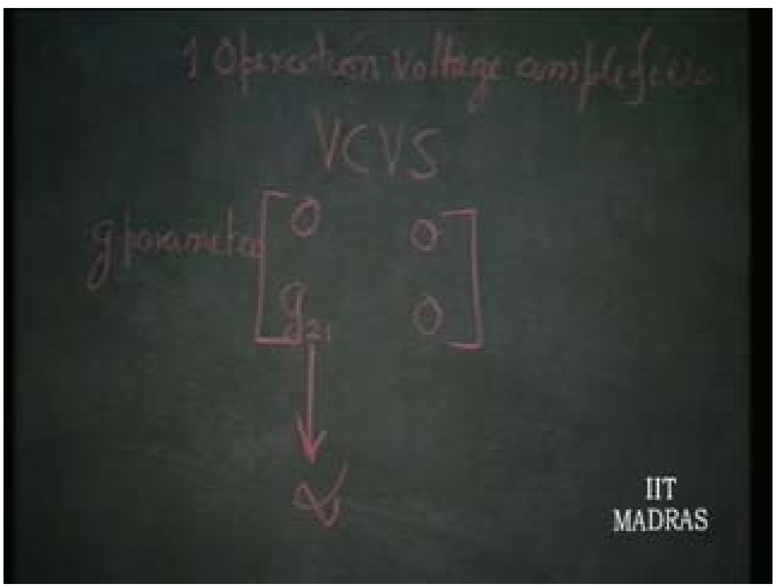

So an ideal Voltage Controlled Voltage Source cannot be represented in any other parameter other than g parameter. If you try to represent an ideal Voltage Controlled Voltage Source by any of the other three parameters then some of the other parameters will become infinity. If you want to represent an ideal Voltage Controlled Voltage Source it has to be represented by g parameters in which if it is to become operational voltage amplifier g_{21} has to go towards infinity. So g_{21} tending towards infinity and all these three other parameters tending towards 0 is the characteristic feature of an operational voltage amplifier that is the starting point.

And here we do not want to get it by means of feedback this should be an open loop configuration which is yet realized such as to make these parameters go towards 0 and this parameter alone go towards infinity. Let us see the essential design features of such a thing.

Now such a design procedure I am going to enunciate can be adopted for design of any of the active building block whether it is used for operational purposes or simply as a controlled source. Now you can discuss different blocks which are going to be used as active building blocks. There are going to be four types of operational amplifiers and four types of controlled sources all of which are useful in analog signal processing. And how ICs went for these can be evolved can be started of from these definitions. Now if you are going to make this go towards zero it is nothing but feedback parameter obviously, this is feed forward parameter, this is input immittance and this is output immittance.

Immittance parameters means immaterial of what the parameter is, so it is called immittance, here this is input self immittance and this is output self immittance. In this particular case it is g parameter here so it will be conductance or admittance and this will be resistance or impedance. So this is made to go towards 0, this is going to 0 and this should go to infinity both of these can be easily achieved by simple operation of the reverse transform parameter for a single device if it is much less than power transform device. One way to increase this and decrease this simultaneously is by cascading. This will increase and this will progressively decrease. In the case of operational voltage amplifier this is nothing but reverse transform parameter that is voltage feedback parameter.

So if it is 10 power minus 3 if you use two stages it would be 10 power minus 6 and if you use three stages it would be 10 power minus 9 so on and so forth. Here one stage has got a gain of 100 so if you use two stages then it is 10 power 4 and if it is three stages then it is 10 power 6. Therefore boosting this and simultaneously reducing this is done by simple act of cascading. So it is necessary that in most of these operational amplifiers cascading is an essential feature for simultaneously improving forward transfer parameter and simultaneously decreasing the reverse transfer parameter.

Here we have to increase the impedance or admittance has to go towards 0. Here we have to decrease the output impedance or output resistance. So we have to take suitable measures to do this. This we have seen earlier in designing differential amplifiers which will be the input stage of any operational amplifier differential input by operating at very low current if they are bipolar stages because RE is nothing but V_t by i_{EQ}.

And i_{EQ} when it is low automatically RE is going to be low but you have to take care that beta of the transistor does not decrease too much. So we should not go to very low current where beta also decreases so that this increase in RE is just compensated for decrease in beta and you do not achieve much of change in input impedance. Thus, input impedance increase can be done by using Darlington pair at the input stage just by using JFET, MOSFET etc. So this is the order in which input impedance can be increased. But we have seen the disadvantage of the input impedance increase.

Remember that, simultaneously offset is going to increase. Depending upon what application is going to be used we will decide whether it is a wise thing to do or not. As far as output impedance decrease is concerned again we have seen that output stage is going to be chosen such that it is a low output impedance stage and automatically the choice is a common collector output stage. So the entire thing can be designed by simply noticing what the ideal device parameter should be and accordingly making use of [….. 38:13]. So output responsibility is given to output stage, input responsibility of input impedance by input impedance is given to input stage then the gain responsibility is given to an intermediate stage.

Therefore, essentially in design of any op amp if you want to do it in a very efficient manner you must have necessarily three stages. The input stage to take care of input responsibilities like input impedance common mode swing etc, the output stage for taking care of output responsibilities like output impedance, output voltage swing and short circuit protection etc if it is needed and intermediate stage to give the required high forward transfer parameter which now does not have the input impedance and output impedance responsibility.

Of course we can put more number of stages so as to boost these up and bring this down but that will result in the order of the system increasing. We would like to have the order of the total system also possibly less than three so that when we use it in negative feedback situations for operational purposes it does not give us trouble in terms of high frequency oscillation. So this is what is called as the third generation operational amplifier, this is a slow process of evolution.

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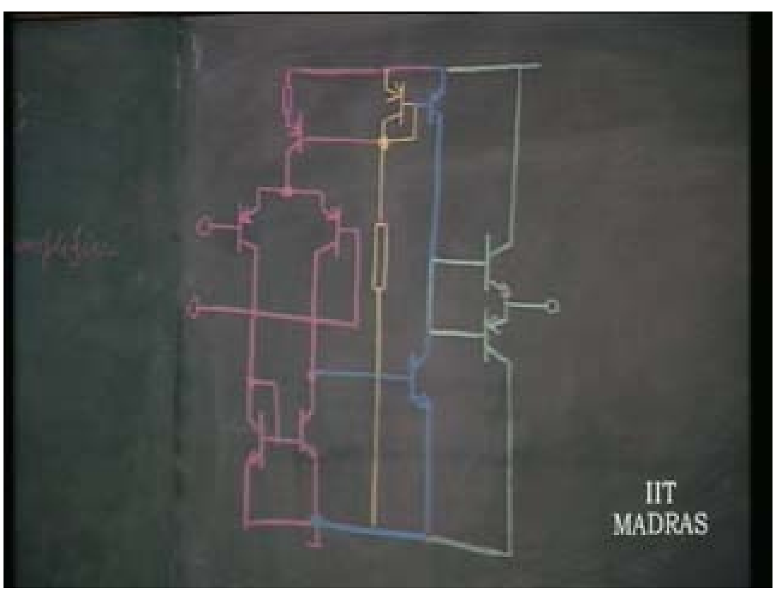

People did not come to this conclusion of freezing this number of stages here to three in one shot. They tried different combinations. The first tendency is simply cascade as many stages of amplifiers as possible. That resulted in serious problems of high frequency oscillation and also this common mode problem resulting in latch up problems etc. So the user had several complaints about the op amp being not suitable in certain applications etc. This kind of thing had to be got rid off and therefore people then said we will give the responsibility of the input to the input stage and the responsibility of the output to the output stage and the gain to the intermediate stage thereby freezing the number of stages of most of these present day op amps into three stages. So we have here the input stage, intermediate stage and the output stage which is common collector. This is nothing but the differential amplifier which we have already discussed, this is nothing but the single common emitter amplifier and this is the way biasing is obtained.