Analog Electronic Circuits
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Lecture – 80
Differential Amplifier: Analysis and Numerical Examples (Contd.)

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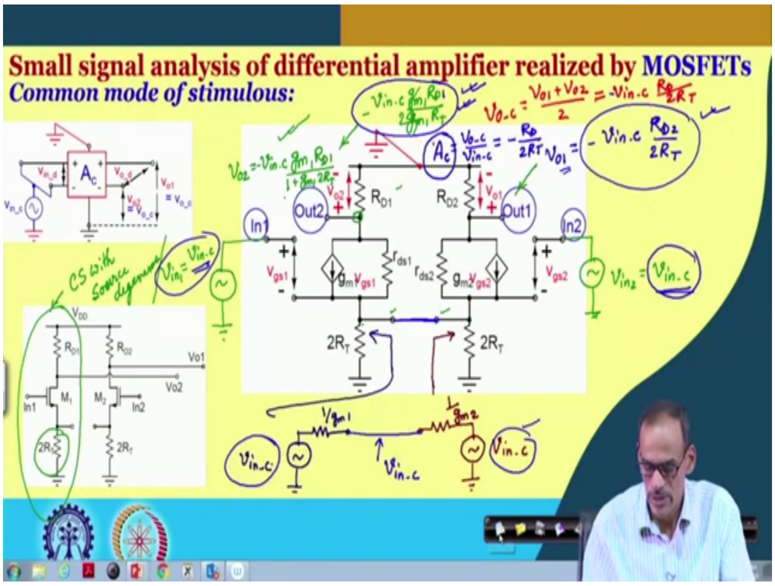

Yeah. So, welcome back after the short break. So, we are talking about the common mode stimulous. And let us see what happens to the circuit when we stimulate the circuit with identical signal at the 2 inputs. And so, here we do have the small signal equivalent circuit and here we like to feed the signal small signal. So, V in 1 equals to V in c. So, same thing same signal we are feeding here at the other input. So, V in 2 equals to V in c. Now for our understanding of the circuit, again we are keeping the circuit disconnected here. And we like to see what kind of signal we do get with this stimulous.

So, if we are keeping this is disconnected and if you refer to the circuit here at the transistor level, this is common source amplifier with degenerator source degenerator. So, this is the source degenerator and we know it is the consequence; namely the signal coming at its output it will be V o 2 equals to the input V in c with a minus sign here. And then g M 1 RD 1 divided by 1 plus g M 1 into 2 RT or you can approximate this by minus V in c g M 1 RD. In fact, this one part you can remove. So, we can simply consider g M 1 and R 2 RT. So, this gm and this g M it is getting cancelled.

So, same thing for the other output, namely V o 1 equals to again minus sign the corresponding input multiplied by RD. So, this is RD 1 this is RD 2 and then 2 RT. So, note that the signal here and the signal here they are identical. Now if I consider on the other hand the signal at the emitter, if I consider the signal at the emitter, it is working as similar to our previous discussion. Before we connect the register and these two registers we do have signal coming here very close to the applied input voltage which is V in c and then Thevenin equivalent resistance it is approximately 1 by g m1.

So, likewise if I consider the other side, this side and what we get it is similar kind of equivalent circuit; namely the signal source, which is close to V in c and then Thevenin equivalent resistance of 1 by g M 2. And note that unlike for differential case, since these two signals the applied signal and the two inputs they are in phase then this signal and this signal they are in phase. Now even if we make this connection, since these two signals they are identical there will not be any change. So, the signal coming at this point it will be V in c.

So, before we make this connection whatever the signal we are having here and here, they are remaining same; even if you make this connection and that is mainly because the input signal it is the applied input signal they are identical and they are in phase. So, I should say that the common mode output if I say if I take average of vo 2 and this V o 1 so, that gives us the common mode output vo c. So, that is vo 1 plus vo 2 by 2. So, that is remaining same as individual 1 namely V in c multiplied by RD divided by 2 RT.

In fact, that gives us the common mode gain common mode gain A c defined as of course, with a minus sign we do have a minus sign here. So, A c is which is defined as vo c divided by V in c equals 2 minus RD by 2 RT ok. So, that is that is the common mode gain. In fact, similar thing you can get for the other differential amplifier realized by BJT.

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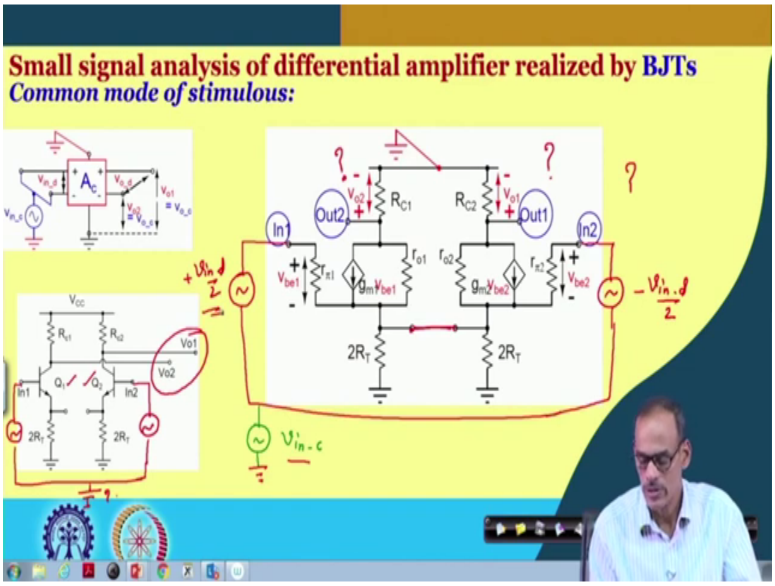

So, in the next slide we do have the corresponding circuit. And here again even though we do have small change small difference in the circuit; namely we do have r pi and r pi here. But all practical purposes when we stimulate the circuit with identical signal here V in c at input 1 and input 2. Then the signal coming here and here they are identical and the signal at V o 2 equals to minus yeah minus gm 1 into RC 1 divided by 1 plus gm 1 2RT into V in c. And same thing we will be getting here also namely V o 1 is equal to minus gm 2 RC 2 divided by 1 plus gm 2 R 2 RT into V in c.

Now, since the signal here and here they are in phase even if we make this connection the signal coming here, it will be remaining unchanged; namely this will be approximately equal to V in c. And as a result this two output after even after making this connection, they are remaining unchanged. And hence V o c it is equal to approximately gm into RC divided by 1 plus gm into 2 RT into V in c with a minus sign. So, you may ignore this one and then you can remove this gm part. So, that will be equal to minus RC divided by 2 RT into V in c.

In fact, that gives us the same expression of common mode gain equals to minus RC divided by 2 RT right. So, in summary we got the expression of the common mode gain and differential mode gain, whenever we will be going into numerical circuit then we will see their corresponding values. Now so, far we are talking about the small signal situation, now you may recall that while we are applying the signal at the input definitely we are also applying a meaningful DC.

So, now next question is that what may be the meaningful DC? Quote and unquote meaningful DC that can be that can be analyzed by considering large signal behavior of this entire circuit. In fact, not only this voltage, but also we like to know what may be the DC voltage coming at the two outputs. And we like to see whether the two transistors really in good condition or not. So, to understand that, we need to have large signal analysis ok. So, before we go into the large signal analysis of course, so, I need to say 1 more thing that. So, far we are we are talking about small signal one at a time namely differential part and then the common mode part.

But then in case you have say both the signals coming together, namely if V in c and the differential part namely plus Vd by 2 and minus V in d by 2; if they are coming together then what happens? So, naturally before we make this connection the situation it was something, but again instead of repeating that, I may directly get into this connection and then we like to see what may be the condition here and here. So, before you go for large signal analysis let me do one more small signal analysis; where we are considering both the common mode and differential mode signal together and we like to see their corresponding output.

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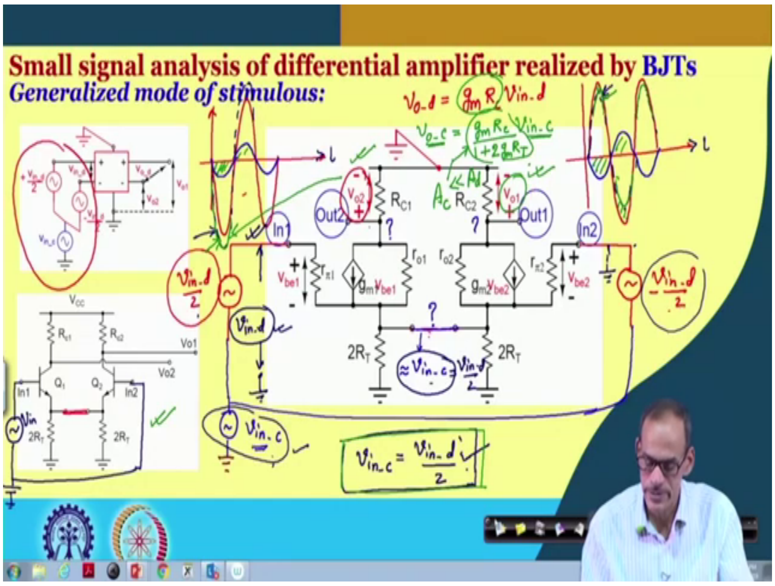

So, in the next slide we do have the generalized mode of stimulous. So, as I said that at the input we like to give both differential and common mode part together. And probably we can make this connection we can make this connection. Now let us see if we apply a differential part here V in d by 2. So, here we do have V in d by 2 and then we do have on the common mode part let me use blue colour. So, V in c which is going to going to the to both the inputs. So, it is going here as well as here.

Now, let us see once we make this connection, then what may be the signal here what may be the signal here and what may be the signal here. Now due to due to this perfect differential sorry, this is perfect differential; that means, we do have a minus sign here. So, these two differential signal is not having any influence. In fact, for differential component this is this supposed to be ground, but then we do have the common mode component. So, the signal coming here, it is only V in c I should say very close to V in c it is slightly less, but it is very close to that.

And then what happens to this output? We do have we do have the this signal it is coming in amplified form. So, this differential part it is it is showing its effect it is in opposite phase. So, likewise here we do have the effect of differential part, which is which is in phase of the differential input ok. And then we do have the effect of the common mode part which is of course, having smaller amplitude. And so, here we do have the common mode input which is again getting flipped. Note that for our simplicity we have considered both the signals are having the same frequency. So, and then if that is the case then at the two output what we will get is the combined effect of these two it may be something like this.

So, this is the net output we do get at this point. And if I consider the other input that will be having the corresponding signal like this. So, you can see that this amplitude it is slightly higher because of the common mode component is coming there and this signal it is slightly less than the red colour. So, we can say that at the output we do have both differential as well as common mode part they are present. So, V o d if I take the difference of this 2 signal we will be getting gm 1 or gm I should say gm into RC into V in d.

And if I take average of these two signals average of say this signal and this signal then what will be getting is only this part, because they are getting added up and the red portion it is getting cancelled out. So, we can say that vo c if I take advantage of the to signal, then vo c equals to gm into RC into V in c. So, that is how the circuit it operates now as a special case, if you consider that let you consider a special case where you would like to give a 0 signal here; that means, if I apply say V in c equals to V in d by 2. So, what happens? So, in this case this part if it is V in d by 2 and then we do have minus V in d by 2. So, together that gives us a 0 signal here.

On the other hand if I am having this signal equals to V in d by 2. So, this V in d by 2 and this V in d by 2 together it gives us V in d. So, the signal at this point with respect to ground it is V in d by 2. So, such kind of stimulous namely if we have a signal only at one side and then other side it is say ground it is referred as pseudo differential stimulous. Many a times suppose you do have an amplifier like this, we like to give signal only at one end and then of course, along with the DC while at the other input we like to give only this DC. And the signal here it is whatever the complete signal you may say that this is V in incidentally that is this V in d. For such case; obviously, you will be getting a signal here which is V in c and this signal it is if you see here it is V in d by 2 and the corresponding signal here.

Because that the common mode gain and differential mode gain they are quite different sorry, I have committed a mistake here V v oc it will be V in c multiplied by gm into RC divided by 1 plus 2 gm into RT sorry. So, since this gain is low, that is why we are getting smaller signal. So, now, in this pseudo differential case, whenever we are considering this common mode signal it is half of the differential signal. Then since this signal it is small the even in this case the net voltage which is this vo 2 and the net voltage here. So, this net voltage here which is vo 1.

Since this part it is very small. So, we can approximate that this output and this output they are almost like a differential. So, based on the logic if the common mode gain this A c it is very small compared to this A d. Then you can say that even if we stimulate the circuit in this pseudo differential form the corresponding output they are very close to like a differential operation and that is why it is referred as pseudo differential mode of operation right. And now we are in a position to go for the large signal analysis.

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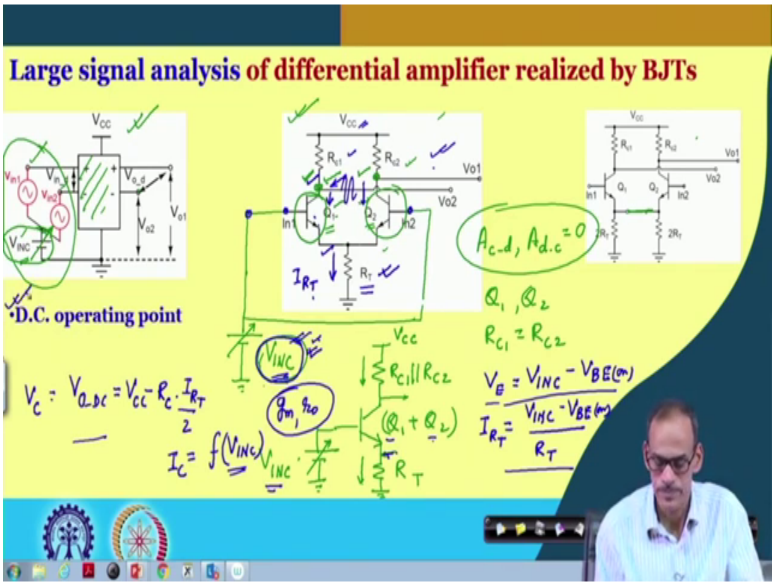

So, in the next slide, we are going to talk about large signal analysis. And we like to see the DC operating point of the amplifier. So, again going back to the circuit here, the basic model here, where we do have the differential amplifier, which is getting stimulated by a pair of signal accompanying same amount of DC voltage. And here we do have the corresponding implementation. Now we are going to talk about what is the role of this DC voltage and what may be the range of this DC voltage and if we vary this DC voltage what may be the situation at the output.

Now, since this DC voltage it is applied to both the input terminal to understand this circuit operation we do not require to split this circuit. In fact, we can keep the circuit like this and at the two inputs. So, at both the inputs we shall apply a DC voltage called V INC and then we will we can observe the corresponding DC voltage here and DC voltage here. So, we can vary this voltage and then we can see what it may happen to DC voltage here as well as here. Now we have so, so we do not require this kind of split. So, we are considering this is connected and hence our subsequent discussion it will be with this circuit we may not be going back to the split one.

Now, coming back to what we said is that if I vary this voltage and then, if we observe the voltage at the two outputs definitely they are also defining the condition of transistor 1 and transistor 2. And for good operation of the circuit we want both the transistors should be in active region of operation. So, the range of this voltage it should be such that both the transistors should be in active region of operation. Now we also have said that to make A cd and A dc to 0; we say that Q 1 and Q 2 are identical and RC 1 equals to RC 2 alright.

And since they are identical probably we can consider the entire circuit together. And in fact, since these two are identical and these two are identical we can see that voltage here and voltage here they will be same. So, we can simply consider it is a folded circuit where Q 1 and Q 2 we can overlap together and then we do have RT here. So, likewise we do have RC 1 and RC 2 they are coming in parallel and here you do have Q 1 and Q 2 they are coming in parallel. And the voltage we are applying here it is this V INC input common mode voltage.

Now, if you if you analyze this circuit of course, depending on this voltage will be getting a voltage here and then that will define this current and that current it is flowing here. So, we do have a DC supply voltage VCC. So, we can make a drop of this voltage and that gives us the corresponding collector voltage. In fact, if you if you go step by step to that for a given V INC. So, what is the emitter voltage? So, emitter voltage at this node or in this you say merged circuit the emitter voltage equals to V IN C minus V BE on. So, it may be around point six or point three depending on the transistors material.

So, that gives us the voltage here and hence the current flowing through this RT equals to V INC minus V BE on divided by RT. In fact, this current it is flowing through both Q 1 and Q 2. So, here also we can say this is IRT which is summation of the two emitter currents and if I say that both of the transistors are identical. So, we can say that half of this current is emitter current and practically they are defining the corresponding collector current.

So, the voltage at the 2 output nodes if I say that VO DC equals to VCC minus RC RC 1 or R RC 2 both are same this multiplied by IRT by 2. So, that gives us the corresponding collector voltage and we do have the emitter voltage. So, now, we have to apply a meaningful voltage here. So, that both the transistor should be in active region of operation, not only they should be in active region of operation it should be having sufficient the voltage here should be having sufficient room for the signal. So, that we can have good amount of signal amplitude it should be able to accommodate.

So, the range over which this range this voltage it is allowed it is referred as common mode range. And in this case of course, it depends on the corresponding value of RT and RC.

So, whenever we will be talking about numerical examples, where we will be having value of this RT and RC and the supply voltage; there we shall see the upper limit and lower limit of this input common mode voltage only thing is that qualitatively. So, these are the expressions, but qualitatively I must say that it is having a good range. So, it is not necessary that we need to have very precise DC voltage here for proper operation, it will be having a good range over which the circuit it will be working fine. Only thing is that depending on this value of this V in c the corresponding collector current it may vary.

So, I should say that collector current is strong function of V IN C and hence all the small signal parameters; namely gm and R naught and so and so, they are strong function of this voltage. But as long as the devices are in active region of operation typically they do not have any problem for proper functionality of the differential amplifier. Now once you get the DC operating point next thing is that what may be the possible signal swing.

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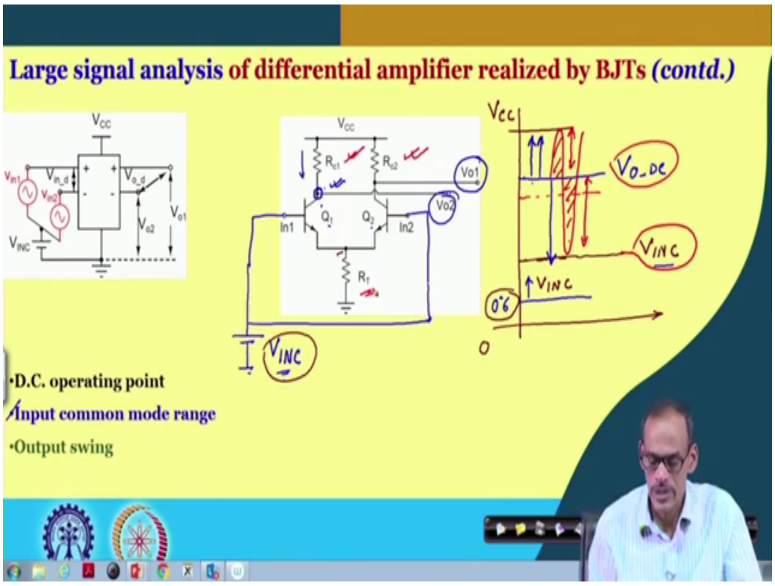

So, let us see in the next slide yeah. So, input in fact, we already have discussed this point the input common mode range.

So, the range over which this common DC voltage it is allowed to vary. Now next thing is that V INC we have this V in c and then what may be the range of this voltage over which, the transistor both the transistors they are remaining in active region of operation. So, if you see the range pictorially suppose we do have the total voltage range. So, this is VCC and this is ground and suppose this input common mode voltage, it should be higher than 0.6 or vb 1. So, that at least we will be getting a meaningful voltage here.

So, V IN C it should be higher than say 0.6 and above so, that is the lower limit of this. And then for a given V IN C we do have some current flow here and then of course, there will be some higher drop. So, the corresponding DC voltage here it may be somewhere here. Now this is VO DC; now this DC voltage it can go as high as or it may go close to the VCC on the other hand it can go as low as suppose we do have some V IN C given to us. So, V IN C we are expecting this should be higher than this lower limit.

So, suppose this V INC it is given to us then the vo individual output VO 1 and VO 2 with respect to this DC it can go as high as towards the VCC or it can go as low as towards the V IN C maybe with a margin of 0.2 or 0.3. So, whatever the range we are talking here this side and this side. So, that is referred as the possible signal swing. Now for a given input DC voltage, we want this DC voltage should be towards the middle of it. So, that the positive swing of the output signal and negatives swing of the output signal they should be equal. So, that gives us the maximum possible not only maximum possible peak to peak voltage, but also that will be helping us to get the maximum amplitude of the sinusoidal signal right.

So, again as I said that whenever we will be going through some numerical examples, we shall explain little detail of how to pick the right value of the resistances and this register.

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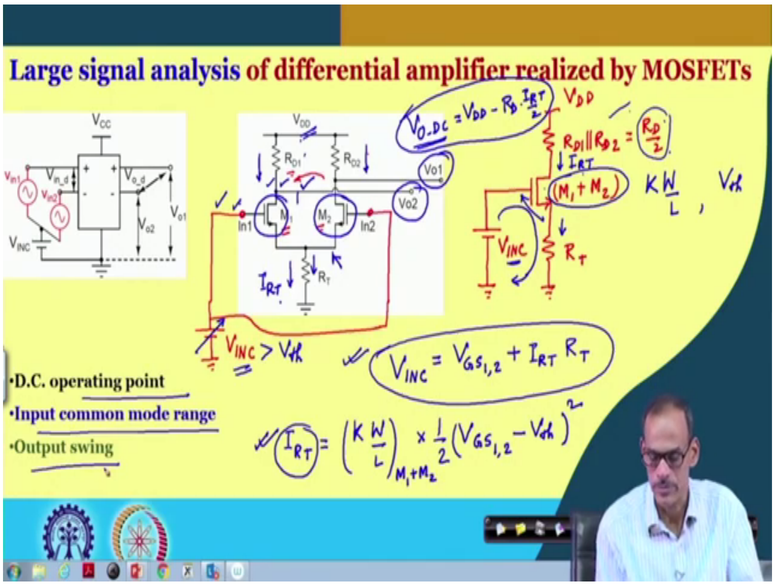

So, similar to BJT for MOSFET circuit also we do have similar kind of situation namely the DC operating point if it is a strong function of the input common mode voltage. So, suppose we do have input common mode voltage coming to the gate or transistor 1 and transistor 2 and that essentially so, this is V IN C. So, that defines the gate voltage here.

Now, again here also we are assuming these two transistors they are identical and these two registers they are identical. And since both the gate nodes they are getting the same voltage probably we can fold it. And we can equivalently say that we do have a single chain; where we do have M 1 and M 2 they are connected in parallel way. And then here we do have V IN C and then we do have we do have RT here and then we do have 2 R Ds R in parallel. In fact, if they are equal you may say that simply RD by 2 and then here we do have the VDD.

Now, at for this circuit if you may recall if we analyze this loop and then if the parameter of the transistors are given namely threshold voltage and trans conductance factor. So, from that we can find what will be the corresponding current flow here for a given value of this voltage. So, if you analyze this circuit what we can say that suppose this circuit the combined registers they do have trans conductance factor of say K W by L it is given to us then it is having VGS and then also if its threshold voltage is given to us then we can say that V IN C equals to VGS of transistor 1 or 2 plus the total current.

So, if I say this is the current is say IRT. So, I RT multiplied by RT. So, this is one equation. Another equation we can get is that IRT should be equal to this K W by L this is combined transistors M 1 plus M 2 together multiplied by half and then the corresponding VGS of transistor 1 to minus V th square. So, we are dropping 1 plus lambda vds part.

So, if you solve see if you consider this equation and this equation and if you solve then you can find the value of this current flow through this RT. And then you can say half of this IRT; it is flowing through this register and this register from that you can find what will be the corresponding drop and that gives us the DC voltage common DC voltage; VO DC equals to VDD minus RD multiplied by IRT by 2 right.

So, that is how we can get the output DC voltage. In fact, either you consider this circuit where the drop here it is RD by 2 multiplied by IRT or if you consider half of this circuit where current is half and the resistance is RD; whatever it is. So, we got the expression of output voltage DC output voltage for a given input voltage. Now again this voltage it may be having a range and this voltage definitely it should be higher than threshold voltage of the transistor. So, that we can get a positive voltage and hence rather it will be having some current flow here and that current flow it will be flowing through this register. Keeping these two devices and active condition and preferably the drain voltage and gate voltage should be such that both the transistors should be in saturation region.

And not only they should be in saturation region, if we have a DC voltage here and DC voltage here it should be such that signal should be having some headroom. So, the again this is also important aspect; but unless we do have numerical values of the supply voltage and registers; probably it will be a little too hypothetical to analyze. So, once we will be going through numerical examples then, we will be talking about the calculation of input common mode range and DC operating point and in the corresponding output signal swing.

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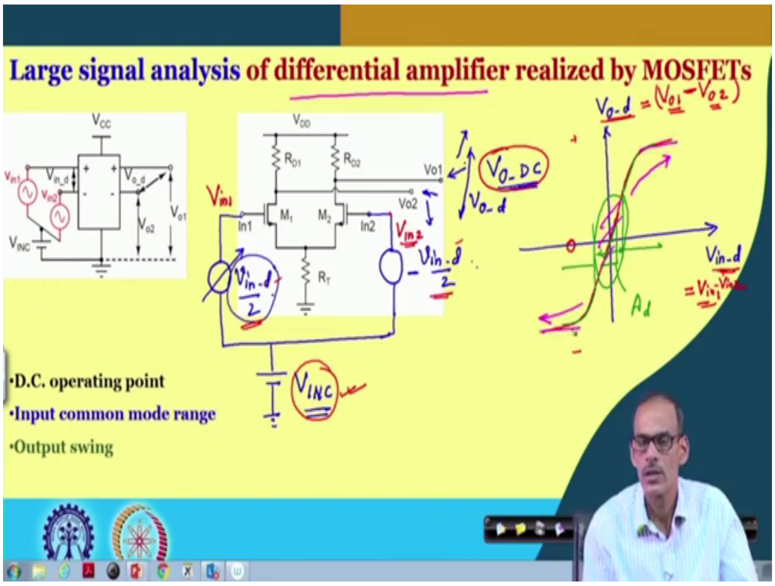

Now, at the input, at the input now if we apply a voltage so, far we are talking about small signal. Now in case if we apply say large signal keeping this voltage constant then what happens. So, if I say that it is perfectly differential namely this is V in d by 2 and this is minus V in d by 2. So, if I make these two signals 0; obviously, voltage here and voltage here they are same namely VO DC and this is of course, V INC assuming that V INC it is having a value which is within its acceptable range and then output voltage it is also having meaningful value.

Now, if I if I increase this voltage subsequently if I am also increasing this voltage with this minus sign. So, what we are expecting here it is, this voltage it is it will increase with respect to its DC and this voltage will decrease with respect to the DC. So, if we plot the difference of these two voltages called vo d with increase of this V in d then what we can get here it is input to output transfer characteristic, but then input it is in differential form and so, is the corresponding output. So, if the input is very small the behaviour here to here it was quite linear.

So, this may be linear, but as you are increasing this input voltage beyond some limit then what will happen is, this may enter into non-linear characteristic likewise this side also it will be entering into non-linear characteristic. And this V o d it is defined as capital V o 1 minus capital V o 2 note that this V o 1 and V o 2, they are representing large signal voltage; both of them are having the same DC voltage of VO DC, but then once we subtract it that got removed. So, range of this V od it is. In fact, positive and negative this is 0 level and this is positive and this is negative.

So, same thing for V in if I am making these two voltages together, but if we are making this voltage it is higher and higher, then we means define this V in d as capital V in 1 minus capital V in 2 and both of them they are having this V INC DC. So, voltage here it is V in 1 capital V in 1 and voltage here it is V in 2 and both of them are having the common DC and then differential part.

Now whenever you are talking about small signal what we have essentially considered it is that range of this input voltage it is small enough. So, that we are talking in the small range and slope of slope of this characteristic curve, it is the gain small signal gain; as we increase this voltage beyond certain range then it may enters into the saturated condition.

So, whenever we are talking about differential amplifier and if we are restricting the operation within this linear range then it is it can be treated an good amplifier having good linearity between input to output. But once you go for an and some other application where circuit is entering into the saturated situation. Then also it is having some application, but the circuit will not be called it is a linear circuit. In fact, then circuit it becomes like a comparator. So, the basic differential amplifier structure can be used for both for amplification purpose for analog application as well as it can be used for comparator.

So, later I whenever the situation permits we may elaborate on that, but just I like to say that differential amplifier whatever the amplifier we have discussed it is having a specific application not only for analog. But it is also having some application called mixed signal where the output it may be more like a logic signal high or low.

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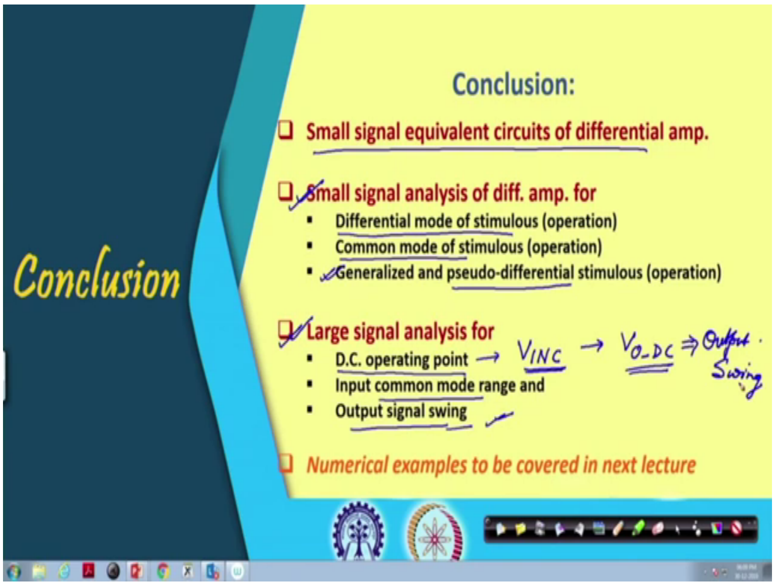

I think yeah that is all we do have. So, to conclude to summarize what we have discussed today, we started with a small signal equivalent circuit for differential amplifier realized in either in BJT or MOSFET version. And then we have talked about a small signal analysis for differential amplifier, specifically for three different modes of operation extensively for differential mode and common mode.

And then also we have talked about generalized stimulous and pseudo differential is a special operation. Then we have talked about the large signal analysis, where we mentioned about the importance of DC operating point. And the DC operating point it is a strong function or the input common mode voltage V INC which also defines the output difference DC voltage. And both this input common mode voltage and output DC voltage and the range of operation of the transistor they are defining the output swing.

So, we did not get a chance to elaborate on these two topics, particularly input common mode range and output showing because it may be difficult to appreciate without any numerical value. So, whenever we will be talking about numerical examples we shall further elaborate on these parameters. And so, our next discussion, it will be numerical examples on differential amplifier, which will be covered in the next lecture; I think that is all.

Thank you for listening.