Analog Electronic Circuits
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Lecture – 05
DC operating point, amplifier design

Hello and welcome back to Analog Electronic Circuits. Today we are going to today's lecture 5 and we are going to talk about how to set the DC operating point of the MOSFET.

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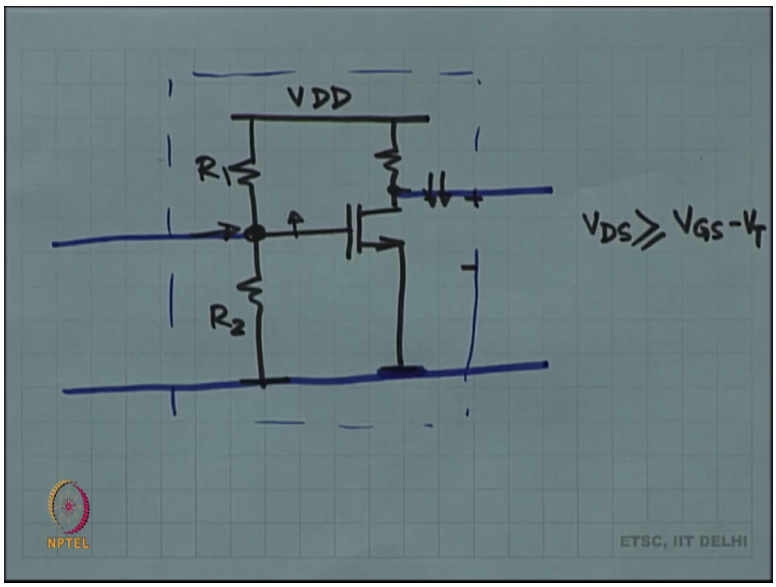

So in the last class that, this is what we were working on and I will just redraw what we learnt in the last class.

So, the first thing we learnt was that if you try to set your DC operating point in this fashion then it is not going to be a good idea, yes you can set some voltage at the gate. So, you get some voltage at the gate because of the potential divider right you can work out the voltage at the gate VDD times R 2 by R 1 plus R 2, but then the same phenomenon that creates gain in the common source amplifier in the amplifier that we studied. The same phenomenon that gives you high gain is going to give you a problem over here.

Why, because if the voltage here is slightly in error slightly higher right. Then the voltage over here is going to be a lot lower and if the voltage is a lot lower than you are at risk of not having net the condition for operating the MOSFET in it is flat region ok. What was that condition that condition was V D S has to be more than V G S minus V T this was the condition to make sure that the MOSFET operates in saturation in it is flat region ok?

And you are at risk of violating this condition may be all that happened was that V T was slightly off from what you thought it would be, and slightly could be a millivolt or 2 millivolts right; 1 or 2 millivolts here and there and you will have a large error at the output note. So, this strategy is not a good idea and we do not do this ok. So, what do we do?

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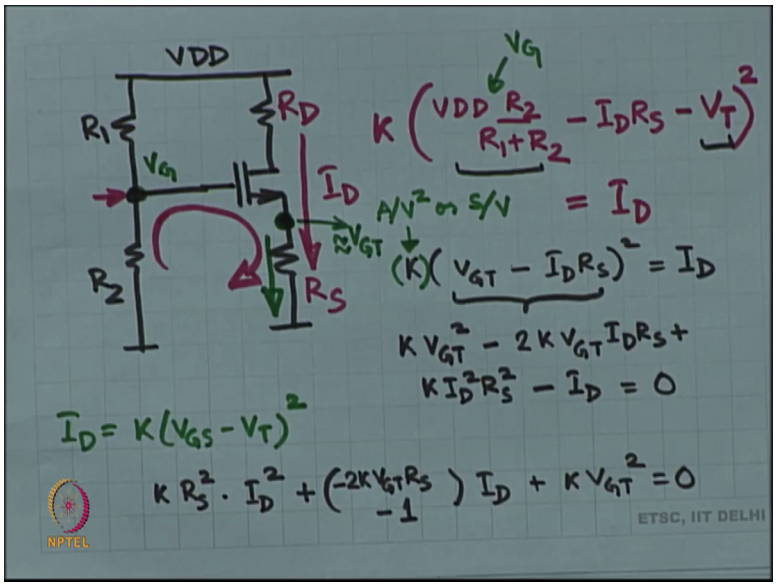

So, we place a resistor on the source all right and now you have to work out a quadratic equation, basically you have to work out this kvl this loop all right. So, the voltage here is nothing it is VDD times R 2 by R 1 plus R 2 ok. This is the voltage here minus the source voltage the source voltage is I D times R S.

So, the gate voltage minus the source voltage gates voltage minus source voltage is VG S minus V T the whole thing times whole squared times K is equal to I D because my equation for the MOSFET operating equation 1 crude model for the MOSFET was I D is equal to K times V G S minus V T the whole squared ok, this was the crude operating

model for the MOSFET and that is ok. Whatever the model is it is and then you plug in that equation and you get the result ok. So, this is your kvl and what do we do we need to solve for I D I D is unknown ok.

So, first thing you can do is combine all of this V D D V T let us call this something what you want to call this, you want to call this V G T is it K times V G T minus I D R S, whole squared is equal to I D right breakup the square. So, you get K times V G T squared minus 2 K times V G T times I D times R S, plus K times I D squared R S squared minus I D is equal to 0 and then pull and all the square terms all the linear terms in I D and all the constant terms. So, you pull in all square terms first. So, you get K times R S squared times I D squared and then you pull in all the terms linear and I D.

So, plus minus 2 K V G T R S minus 1 and, lastly the constant terms and then what is the next step? The next step is to say is to use your quadratic formula and work out the result. Now, I am going to after doing this I will do a much simpler method as well and show that the results are very close to each other ok, but let us do the accurate one first.

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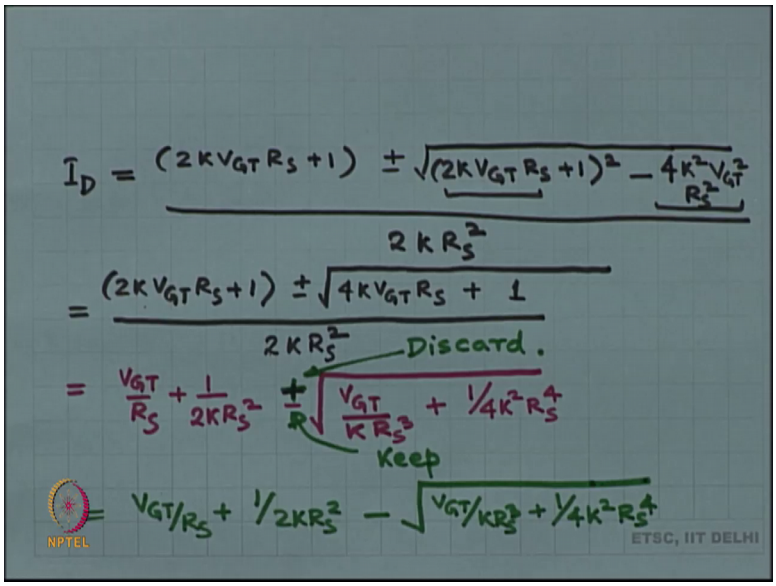

Ok. Have I done it correctly I think it is correct right this is your quadratic formula. So, minus b plus minus square root of b squared minus 4 times A C by 2 A all right. And here what do you see the first thing that you see is that in this whole squared this and the minus cancel out.

So, that is very nice and then you can expand the whole squared all right. So, this is done. Now, what can you say there is a plus minus are there 2 answers to this are one answer can there be 2 answers well the math's tells me that they could be 2 answers, but does it happen in physics are there 2 answers in reality practical in the practical situation will you have 2 answers look at this. So, one of the 2 routes 2K V G T R S plus 1 plus some staff, and in the other case you have got minus a square root could it be could it just be that the minus root cannot happen, because this term is larger than the other 1 and I D cannot be negative.

So, let us just simplify a little bit and then you will see for yourself. So, the 2 and the square root of 4 cancel out. So, what you see over here the first term V G T by R S squared is V G T squared by R S squared over here I have got V G T by K R S cube, the second term 1 by 2 k R squared and this is the square of that all right.

So, do you think one of the 2 routes is not going to be possible be practical because I D we will somehow workout to be negative I D cannot be negative or do you think V G S, V G S minus V T is going to work out to be negative actually the later is what is true the current is going to work out to be; So, large that you need negative V G S minus V T to make it possible.

So, for example, if you pick the plus root over here if I pick the plus root if I choose the plus root, then what is going to happen is this is going to be large right the I D is going to be large. Now, if I D is too large then V G S minus V T V G S minus V T is V G T minus I D R S is going to become negative if I D is too large or square of that is still positive. So, mathematically it is acceptable all right, but unfortunately physically it is not practical, because I D is too large right V G T minus I D R S becomes negative ok. Now, if I do that if V G T minus I D R S whole squared still remains positive k times something positive is something positive. So, there that still works out well for me, but in practice that is impractical.

So, the plus root over here has to be discarded all right. The minus root is what you have to keep ok. What you are going to find out is that the staff underneath the square root is actually not more than the stuff that is outside the square root it is actually less. So, the minus will still keep some positive value over there. So, it is fine. So, I D can still be positive even when you keep the negative sign over here all right anyway.

So, finally, what it boils down to is I D is V G T by R S plus 1 by 2 K R S squared minus square root of some stuff. Shall we proceed further all right. Now, the hallmark of a good transistor is going to be a large value of K K is supposed to be some quite significant. First of all you cannot really say K is large K will have some dimensions right what is the, what are the dimensions of K?

Current amperes per volt squared or Siemens per volt you can choose appropriately, but typically this quantity is good transistor has a large number over there large number of Siemens per volt all right. Just letting you know because we are going to play a trick over here. If you say that K is significant right then what is the relationship between V G T by R S and V G T by K R S cube, which one is much smaller is there something that is much smaller than the other think about it.

So, the simplified analysis is as follows. So, this is this in this with this technique you get to find out what is exactly I D? Ok. You solve KVL you solve KVL over here Kirchhoff's voltage law and you find out the value of I D. So, this is the standard way of doing things.

However, let us say you are at an exam or let us say it is not even an exam let us say you know you have to give a quick answer or you have to reconcile the numbers very quickly and figure out whether this is correct or not correct and so on and so forth ok; So, quick estimate in the engineering approximation.

So, this engineering approximation that we are going to do is by assuming that K is so, large that V G S minus V T this is V G S minus V T is small to keep I D to some reasonable value. So, I D is a reasonable value, which means that V G S minus V T has to be small, because k is large k is large V G S minus V T has to be small then only I D is reasonable.

So, if I assume that K is large then V G S minus V T is more or less equal to 0 which means V G S is about V T or a little bit more than that. So, this is the approximation. So, you assume that V G S K is so, large that V G S is more or less equal to V T it is not less than V T it is more than V T slightly above V T ok. And that happens to be not very unreasonable I will tell you what is even more reasonable to assume.

So, in such a scenario do you even have to solve this KVL it turns out that the KVL becomes far simpler, if you assume that V G S is more or less equal to V T all that you do is work out the voltage here that is V G equal to R 2 by R 1 times VDD.

And, then what is the voltage here V G S is more or less equal to V T, which means the voltage over here is V G minus V T. Basically the voltage here is V G T approximately, which means that I D is approximately V G T by R S, that is all right.

Now, what is all the other stuff then if you plug in K to be large this is small plug in K to be large this is small, K large this is small. So, all of these terms go away, if you say that K is large ok. So, the only term that remains is V G T minus R S where V G T you have computed what is V G and V T you know. So, V G minus V T that divided by R S is more or less equal to the current ok. All the other terms are much smaller all right.

Whenever you do this larger smallest thing I am doing it very crudely over here I did it very crudely whenever you do these larger and smaller things then you have to have larger relative to what? Smaller related to what? Ok. So, be careful this was a very crude way of doing things ok. However, this approximation works 2 0 th order to first order you can make yet another approximation.

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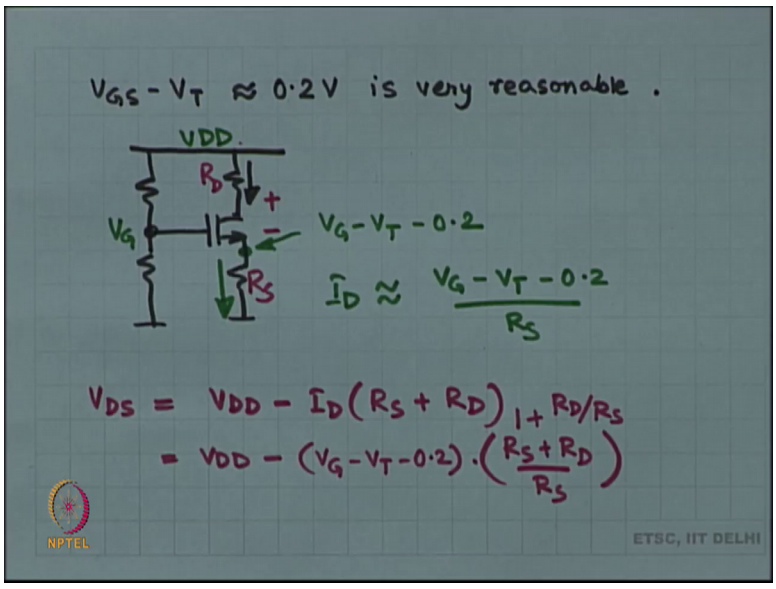

It turns out that V G S minus V T of approximately 0.2 volts is very reasonable ok, by the way. If you are in an exam and you do not have time, if an in an exam and you have time

then do this whole thing right do this proper way of doing things you will get full marks ok.

If you do not have time or if you are trying to answer a multiple choice question right find the answer nearest to this result, or even better find the answer nearest to this right assume V G S minus V T is 0.2 volt and then find the answer nearest to that.

So, I will draw my circuit again we said this is vg and this is rs ok. So, if I assume that V G S minus V T is 0.2 volt, then the voltage here is vg minus V T minus 0.2 and immediately I D is that divided by R S all right.

So, this happens to be a first order approximation 0.2 volts is a very reasonable value of choice for V G S minus V T. So, over here 0 th order approximation was just say V G minus V T by R S, that gives you know really 0 th order approximation, better slightly better approximation, not significantly better approximation, would be to assume that you have got 0.2 volts over there and then solve it all right.

However, this is the accurate result and if you have time at the exam then do it is, if you do not have time I would suggest go for 0.2 right. Assume V G S minus V T is 0.2 all right and that automatically will give you everything else ok. So, what is the story so far. So, far I have been able to I have manage to compute the value of I D all right.

If I can find out the value of I D, I D is now related to V G V G T V G minus V T ok. Earlier what was the scenario? What was my problem earlier? My problem earlier was a small error in V T would have created a drastic error in the output voltage or rather in V D S a small error in V T would have created a large error in V D S, and that would take my device outside of it is flat region outside of saturation. So, this was my primary worry. Now, let us see does this circuit solve that problem.

So, let us say V T has some error keep worrying about I mean the error source of error is V T over here ok. So, I D is more or less going to be equal to this right. The same I D is going to come through R D right. And if I look at a KVL on the output side on the drain side I do a KVL V D D minus I D times R D minus V D S minus I D times R S is equal to 0 or in other.

words V D S will be equal to V D D minus I D times R S plus R D ok. That is what is left for V D S.

Now, I D happens to be something of this fashion. So, therefore, I will get V D D minus so, if there is a delta error in the value of V T. Suppose V T is of by 1 millivolt when V D S is going to be of by 1 millivolt times R S plus R D by R S and as long R S is not 0, if R S is 0 then you are done for right.

If there is the smallest error in V T then you know you get a very large error in V D S, which was earlier case R S was 0, but if R S is not 0 then the error in V T is controlled right. So, 1 millivolt error in V T I can keep it keep the whole thing in 2 millivolts if R D by R S is one for example, if R D is equal to R S then the error in V D S is just 2 millivolts, which is not bad.

So, this is the much better circuit to start with why is this much better circuit to start with because a small error in the value of the gate voltage or in the value of V T of the MOSFET is not going to create a large error in V D S. And V D S is something that matters to us because V D S has to be more than V G S minus V T to make sure that the device is in it is flat region.

In it is in saturation and why do we have to be in saturation, because I have said. So, I have said that analog circuits have to be in saturation and that is why you have to be there all right good.

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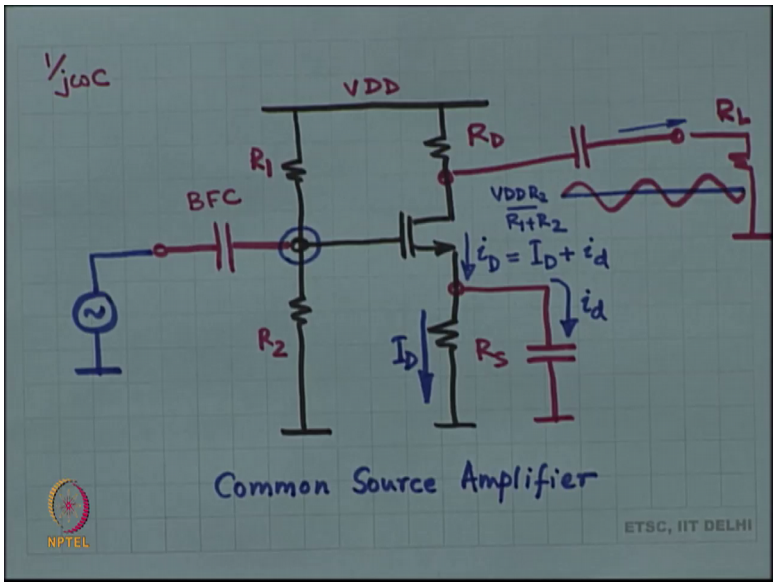

So, this is the circuit with which we have established the DC operating point ok. And the DC operating point has to be established in a way that V D S has to be more than V G S minus V T. And once you have done that you say that your job is done.

So, you select values of R D R S and so on such that you establish V D S to be more than V G S minus V T. Now, what we have to make an amplifier out of this right and my amplifier circuit did not look like this my amplifier circuit looked different, this is how it look like right I applied the signal over here I measured out at the drain and so on and so forth all right.

So, the first thing that comes to mind is that the amplifier looks different R S does is not there. The second thing is that the amplifier involves a small signal remember from the last class we did the small signal incremental model of the MOSFET, we looked at it and said that this is what we want right the small signal incremental model we place it over there and then we do the circuit analysis and we find that there is a gain in the amplifier ok. You found a gain of minus one hundred or something right. So, the signal that has to be amplified is a small signal.

How do we get the small signal into the circuit? And here what we are going to use is an element called a capacitor you are all familiar with capacitors, but these capacitors are going to be special they are big and fact ok. So, we can call them BFC. So, this capacitor is a BFC big fat capacitor ok.

So, it is. So, big and. So, fat that if you are not happy with how big and fat it is make it bigger and fatter ok. Now, why did I place the capacitor over there? The reason why I have place the capacitor over there is for it is property that the impedance of a capacitor is 1 by j omega C remember right, that is the impedance of a capacitor.

Now, if omega is 0 then the impedance of a capacitor is an open circuit omega is 0 1 by j omega C is infinite and therefore, this capacitor starts behaving like an open circuit, but if omega is not 0 if omega is 100 radians per second, 1000 radians per second, 1 giga radian per second, then the impedance of the capacitor become smaller and smaller and smaller.

Now, we are going to assume that the value of C is so, large that all that at all frequencies of interest ok. All values of omega that are interesting to us this capacitor behaves like a short circuit ok. So, if you are not happy with the value of c make it bigger increase the value even further one farad whatever you want ok.

So, that is the role of this big fat capacitor it is a short circuit at omega not equal to 0 open circuit at omega equal to 0 or in other words it is a short circuit for AC and open circuit for DC all right. So, this element is going to be used again and again. So, what happens? Now, I am going to apply my signal over here and my signal is an AC signal a small AC signal and incremental AC signal right. AC is important, because we are making the distinction that the signal is changing with time ok. And if it is changing with time the big fat capacitor will behave like a short circuit for this particular signal.

But, for the DC operating point established by R 1 and R 2 over here the voltage over here is V D D times R 2 by R 1 plus R 2 right for the DC operating point the big fat capacitor is an open circuit. So, it does not matter all right. So, this is the role of the big fat capacitor over there. So, therefore, what is going to be the voltage over here? This voltage has 2 parts, 1 part is coming from V D D and R 1 R 2 the other part is coming from the signal.

So, as far as the signal is concerned this is a short circuit as far as DC is concerned this is an open circuit right, which means that the voltage over here is this signal riding on top of the gate voltage the operating gate voltage. So, suppose I had the operating gate voltage as V D D times R 2 by R 1 plus R 2 or vg or whatever you want to call it. And

suppose my signal over here was some small sin wave; then the voltage at the gate is going to be that sin wave riding on top of the DC operating point.

Is this understood is there any problem no problem good. Now, this is the gate voltage that you are applying and that is exactly what you wanted earlier right. In the last class when we had done this amplifier, we had applied a voltage and on top of it we had a small signal riding on top of a DC operating point, that is exactly what you have got over here ok.

So, this wonderful right, the next thing is R S we have to sort out R S and again we have going to use a big fat capacitor to R S cube all right. So, what does this mean? This means that as far as the DC operating point is concerned, this capacitor is an open circuit and therefore, you do not worry about it you established the DC operating point, but when it comes to the signal the signal is AC and this capacitor is now going to behave like a short circuit for the signal and therefore, none of the signal current is going to come through R S.

So, this is a short circuit, which means that the source is going to be effectively at 0 volts this is at 0 volts as far as the signal is concerned and that is exactly the same as our old circuit all right. So, in other words what is happening over here is that you have got a current I D equal to the DC operating point current the signal current and this breaks up into 2 pieces the DC operating point and the signal ok.

So, this capacitor is being used to split up this combination current, which has both DC operating point and the signal. So, that is being split into the DC operating point current and the small signal current the signal current that is the job of the capacitor over there fine so far so good ok. Then the next thing is that you do not want to observe the DC operating point at the output and that also is going to be sorted out with the help of another big fat capacitor right.

Let us put our load over here. So, this is also a big fat capacitor and this current is purely AC that is purely signal current is going to go this way right. The DC current is not going to come out through the load. So, the load is therefore, only going to see the ac current it is not going to worry about the DC operating point.

For example, you can connect this to an oscilloscope and you will observe this AC signal current times R L you will not see any DC operating point over here ok. So, this is the common source amplifier a similar amplifier made with the bjt it is called the common emitter amplifier, this is called the common source amplifier all right. And the reason why it is called common source is not very obvious right, now the reason why it is common source is because this is the basic structure of the amplifier. And here the input as well as the output are referred to the source.

The source is at ground ok. So, you apply the input between the gate and ground, you apply you watch the output between drain and ground right source is at ground. Therefore, this is called a common source amplifier the source is common to both input and output ports. So, this is the 2 port network.

So, this is the 2 port network you have got an input port you have got an output port and the source happens to be the common port. So, that is why this is called a common source amplifier all right very good. So, this is our first amplifier the common source amplifier and after the common source amplifier the natural statements are going to be, that like the common source amplifier we should be able to build a common drain amplifier a common gate amplifier and so on and so forth right, because those 2 terminals also exist.

So, I will summarize the common source amplifier briefly.

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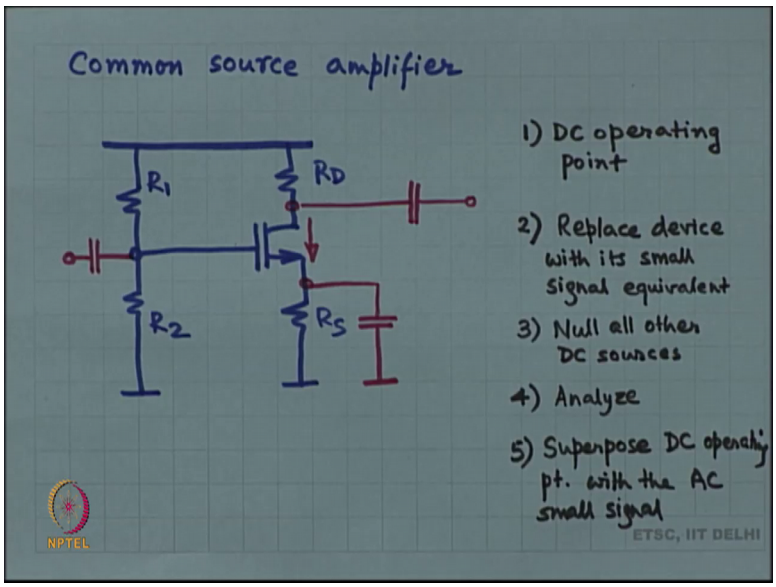

So, the first thing to do is to establish DC operating point; established DC operating point using a circuit that does not look like the amplifier at all. Typically this is the circuit that is always going to be used to establish the DC operating point. The reason why is because the anything else might create fluctuations in V D S and might take the device outside of saturation.

So, this circuit is common. Now, that you have established the DC operating point, what we are going to do is we are going to apply the input, which is ac and it is a small signal it is going to ride on top of this DC and it is going to create a perturbation in V G S. Now, we want this perturbation to be completely across V G S not V G S and R S. So, therefore, we place for maximum benefit we are going to place one more capacitor over here.

So, then any perturbation over here is going to come completely across V G S. This perturbation in V G S is going to create perturbation in I D right and this perturbation in I D should be captured at the output. So, you want to watch the output over here, if you watch the output over here then you get a DC operating point plus the perturbation in the drain voltage. If you do not want to watch the DC operating point, then you place another capacitor and then you get to watch just the perturbation in the drain voltage ok. So, this is the more or less the idea. Now, the way you analyze the circuit is to first find out DC operating point.

So, first you established the DC operating point right. Then in the next step we are going to focus on the device and replace it with a small signal equivalent model of the device. So, we have not yet done it nicely right. I am going to do it further, but this is going to be the strategy.

Now, when you have done it you will also apply superposition and null the DC sources like this power supply voltage over here, then you are going to do the analysis and then finally, super pose the DC operating point with the AC ok.

So, this is going to be the strategy that we are going to follow all right and let us stop for today, because in the next class what we are going to do is we are going to look at the small signal model right me this number 2 point right. So, far we have established the DC operating point. We know how the amp the common source amplifier looks like we have some basic idea of what it is going to how it is going to behave right? And then now

what we are going to work out is a small signal equivalent model of the MOSFET right and work out the rest of the analysis. So, let us stop here.