Analog Electronic Circuits
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Lecture – 17
Analysis of simple non - linear circuits containing a MOSFET (Contd.)

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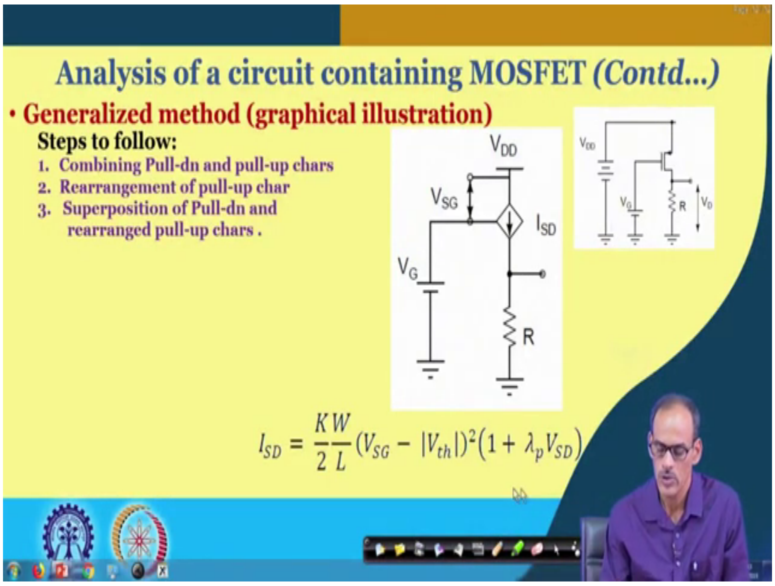

Students welcome back to the topic of Analysis of non-linear circuit containing MOSFET after the short break. So, we are discussing about what will be the generalized method whether the signal or the input is applied to the NMOS or PMOS. And, we are discussing about the situation when the circuit contains the PMOS and the on the other hand the load as you can see here it is PMOS, and the load it is connected to ground and so and so.

Now, let us see some numerical not numerical different situation, if the voltage it is changing at the gate and then what happens. So, for a given value of the gate voltage and the parameters of the device we understand that how to find the solution. And in case, if the voltage it is changing then what happens to the solution point. In fact, this is similar to whatever we have discussed with the circuit containing BJT.

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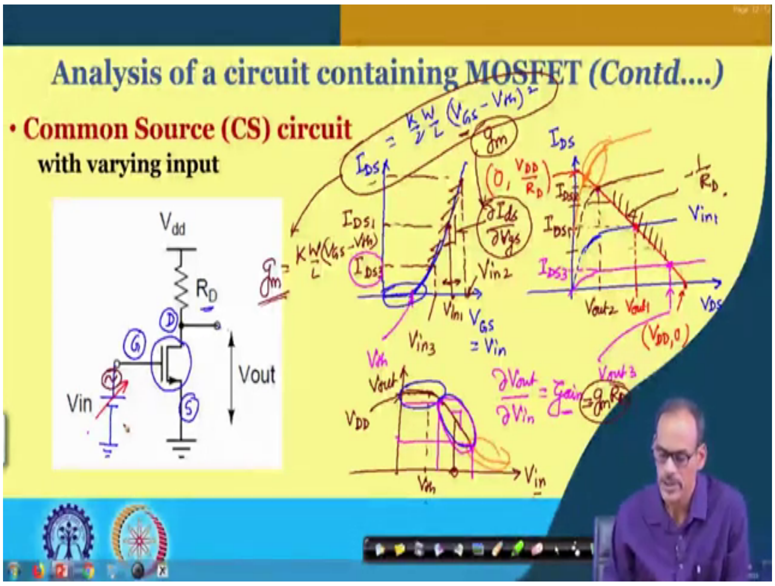

So, let us do the similar kind of exercise and we will see whenever the differences are there we will be highlighting that. So, this is the circuit of our consideration that we do have the N type MOSFET, the signal or the input you are applying at the gate. The source node it is connected to ground and drain it is connected to the, towards the positive supply through this resistance call R D.

And at the input, so, let you consider different situation. In case this input voltage we vary with time, then what happens to the output voltage. So, as we have discussed so for a given value of V in what we can do, we can draw the I V characteristic or the device or you can say that output port I V characteristic.

And so, this is I DS versus V DS and this is of course, for a given value of V in calls a V in is equal to V in 1 and the load line it is given by this straight line. So, one point here it is V DS is equal to V DD. So, that point it is referred as V DD and 0 current and on the other hand this point it is currently it is so, voltage it is 0, but then the current is V DD by R D. So, that is the R D here.

So, the slope of course is 1 by R with a minus sign and what we said is that wherever they are intersecting that gives us the solution point. So, wherever they are intersecting that gives us the V DS solution or you may say that the corresponding V out.

So, now for a given V in, say V in 1 how do you find the current? So, then we need to consider the input to output characteristic namely I DS versus V GS or in this case V GS it is same as V in. So, you may say that this is V GS which is equal to V in and we know that this is square law namely K by 2 W into W by L into V GS sorry, yeah. So, this equation it is you know what we say that K by 2 W by L V GS minus V th squared.

So, I consider only this part, I am ignoring this 1 plus lambda V DS part. So, for a given value of V in say this one V in, we do have this current. So, that current is basically defining this level and then the load line wherever this load line is intersecting this current that gives us the corresponding out. So, you may say that starting from this point called V in 1 that gives us I DS 1. And, then this I DS 1 it is getting reflected here and then the corresponding output here it is out 1.

So, now if I vary this voltage, say if I increase this voltage to some other value say V in V in 2; so, this is V in 2. So, that gives us different current say maybe at a higher value like this. So, this level of this current it is I DS 2 and wherever they are intersecting that gives us the output voltage namely the V DS. So, that is the V out 2.

So, likewise of course, here you can see that the device it is almost entering into the triode region and beyond that if you do then of course, there will be heavy non-linear part, we will be discussing that shown. So likewise if I; on the other hand if we decrease this V in to a smaller value namely V in 3.

So, then the corresponding current here it is I DS 3 and then this I DS 3 it is producing. So, I DS 3 it is producing another current level here and the corresponding characteristic curve may be somewhere here. So, this is I DS 3 and wherever they are intersecting that gives us the other V out called V out 3.

So, as you can see that if V GS is higher than threshold voltage V th, then we can see that this characteristic it is going up or down and, making this intersection point of the device characteristic with the load line going up and down, but then along this load line and making the variation of the corresponding output. So, for different values of V in if I observe the corresponding V out what we can get it is input versus rather input to output transfer characteristic.

So, we may say that x-axis is V in and then y-axis is the corresponding output and whenever the V in it is higher than V th, then the current starts flowing, the voltage it will be maybe close to V DD, but of course, it starts dropping. But before that so, here so, this is V th and beyond this point the voltage starts deviating from the V DD level. And, if the V in is less than V th current is 0 here and then the output it is of course, V DD.

So, as we are increasing this V in beyond V th this non-linear characteristic curve it is basically some extent it makes it non-linear, but then this part you can say fairly linear. And, then if you increase this V in beyond some point then of course, the device it will be it may be entering into the triod region and incidentally this crossing point it may be close to 0, but it will not be going to 0. So, you can see that beyond some point this part it will be entered into the non-linear side.

So, here the you may say that this portion this non-linear portion it is due to this part and on the other hand this non-linear part of the characteristic curve it is due to the device entering into the triode region. And, in between in between you can get a nice portion of the characteristic curve namely this portion. Let me use a different color for this part.

So, this portion it is a very good part. Namely, if I change the input here then the corresponding current variation here you can say that it is fairly linear with that voltage and here of course, the load line is linear. So, that makes the input to output, input to output relationship it is fairly linear.

Now, this slope of this line namely change in V out with respect to V in that gives us the gain; that means, if I vary this input by some amount how much the corresponding effect will be observing at the output that gives us the gain. And, as we have discussed for b j t circuit here this gain it is it primarily depends on the slope of this line. So, you can think of it as a mirror.

Suppose, if we are changing the input voltage with respect to a point say V in 1 here in this case, then if you vary this input centering this V in 1. Then based on the slope of this line, you can get the corresponding current change and that current change is coming here and then that current change again getting reflected by the load line to the voltage axis.

So, you may say that voltage to current variation and then current to voltage variation. So, here the slope of this line, it is basically the change in I ds with respect to V gs. And, this is basically defines the trans conductance of the device denoted by g m trans conductance.

On the other hand this slope of course, it is the slope it is minus 1 by R D. So, these slope when we say it is basically voltage to current slope is this one, in other words current to voltage slope or current to voltage transformation it is basically R D. So, if I consider slope of this line and then inverse slope of this line that gives us the voltage gain here.

So, the gain here it becomes actually g m multiplied by R D with of course a minus sign. So, how do you find the g m? So, that we will see later, but just to give you a hint that if I consider say this I V characteristic. And, if I take derivative of this I DS with respect to V GS, I can find what will be the corresponding g m.

So, if you if you use this equation you can find the expression of g m it is equal to K W by L into V GS minus V th. So, if you multiply this g m by this R D that will be giving you the gain of the circuit. So, in other words if I see that at the input instead of giving varying input, if I consider a signal riding on a DC then at the output we can get signal riding on a DC.

So, let me further instead of a complicating these slides further it is already becomes clumsy. So, let us go to the next slide and start with a fresh look into the circuit.

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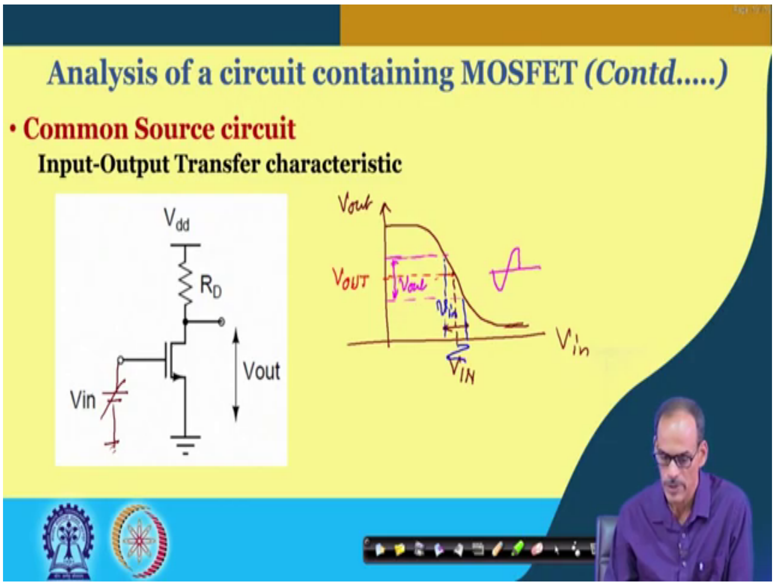

So, what we like to say that; so, we already have discussed the input to output transfer characteristics. So, this is the input and if we vary this one what kind of output we obtain. So, I will not be further repeating that detail, but you may recall that we got input to output transfer characteristic is like this. So, this is V in and this is V out.

And, then if you consider that input we are changing with respect to a DC voltage nothing, but say V capital IN and then if we vary with respect to that by some small amount, it may be called small v in. And, the corresponding effect, what we get at the output is when you have a DC level here called V capital OUT. And, the corresponding signal we may get with respect to that DC level depending on how much the variation we are giving here and that may be called v out.

So, if you are applying input here at the input at the gate or gate to source some signal here. The corresponding effect we are getting at the drain which is in fact, it goes down and so, it goes down first and then it goes up like this. So, yeah; so, this input to output relationship it can be say that, that is the gain. So, we may think of that this circuit it can amplify the signal and yeah so, this is what we mean, sorry instead of going to the amplifier gain I have framed one numerical problem to find the operating point and so and so.

So, let us solve this one first and then we will be going to the notion of gain. So, the next numerical example associated with this circuit is given here.

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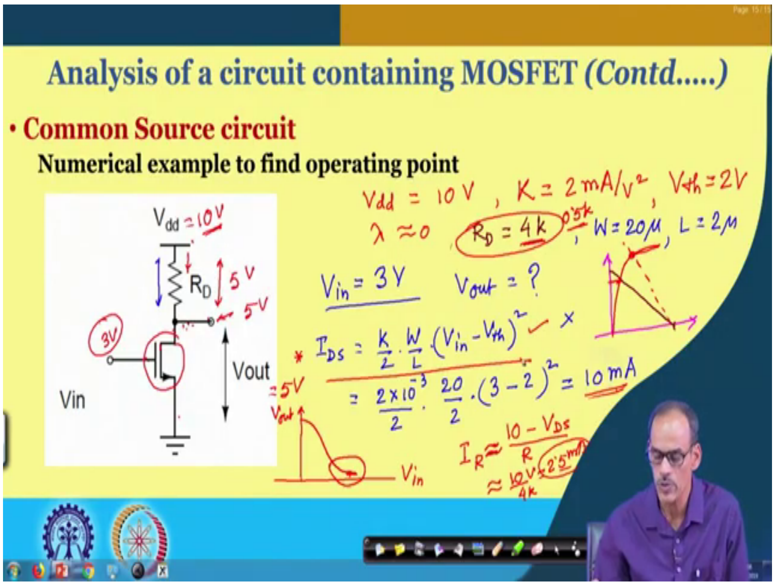

So, let me give some important parameter here to solve the numerical problem; say, say we do have V dd let me use a different color. So, say V dd is given to us say 10 volt, the device parameter say K is say maybe 2 milli ampere per volt square, then V th of the transistor it is a 2 volt and maybe lambda we can approximate to be 0 to simplify.

And now, let us see the V in, this capital V small in if it is say 3 volt and I need the other information particularly R D also. So, let you consider this is 4 K, then with this condition V in can you find what will be the V out. So, we need to find the corresponding value of the V out. So, how do you proceed?

To start with we assume the device it is in saturation and later on of course, we have to verify it; otherwise, we have to use triode region equation. So, if I assume the device it is in saturation. So, directly then we can write I DS; I DS equals to K by 2 W by L into V GS that is actually V in minus V th square and, ok; I need this W by L information as well.

So, for the time being let you consider W it is say 20 micron and L is say 2 micron. So, with that what you are getting here it is K is equal to 2 milli 10 to the power minus 3 and by 2 W is 20 L is 2 V in is 3 minus V th and square. So, what we are getting here it is 10 milli ampere? Now, if you see if 10 milli ampere it is flowing through 4 K then of course, the drop here it is expected to be a 40 volt then of course, then this is not valid, ok.

So, now let we change the value of this resistance. So, this will not work out. So, let you consider this is 0.5 0.5 K, then what will be the situation. So, if I again if I start with this assumption the device it is in saturation region and then the currents should be 10 milliampere. So, the voltage drop across this R with 0.5 K, it will be 5 volt, yeah; so, 5 volt and we do have 10 volt here. So, we do have 10 volt here. So, the voltage coming here it is 5 volt, voltage here it is 3 volt.

So now, if you consider the gate and the drain voltage; drain it is higher than the gate voltage itself; that means, the pinch of it is happening; so, then this equation is valid. And hence, you may say that the voltage here V out it will be 5 volt. But of course, with 4 K the device it will not be really in saturation region. In fact, you may recall that we are talking about input to output transfer characteristic curve, it was like this.

So, the V in, in this case V in and combination of this resistance if it is say 4 K what we are doing here it is the device it enters into the triode region so; that means, the device it was actually in this region dip into this triode region. So, as a result the pinch of it was not happening. This drain voltage it is very close to ground and then in that case you may say that if this voltage it is close to ground. The current flow on the other hand it is approximately 10 volt minus close to ground divided by whatever 4 K.

And in that case the I R is approximately 10 volt minus whatever the V DS, it is approximately. So, let me write this is equal. So, 10 volt minus V DS divided by R and this can be well approximated by 10 volt divided by 4 K. So, that gives us 2.5 milliampere. So in fact, this is quite different from the required current in the saturation region.

So, if you try to correlate the graphical interpretation of the input to output situation. So, the device; in fact, let me let me draw the load line first. So, the load line it is based on the value of the R we are getting it low. And whatever the 3 milli ampere of current sorry, 3 voltage 3 volt of the gate voltage the device actually already enters into deep triode region like this. So, even though this current it is expected to be 10 milliampere, but actual current since it is deep triode region that is much lowered here.

So, on the other hand if you decrease and the value of the resistance; in fact, that makes this line the load line more stiffer and that makes this corresponding operating point it is bringing the device into the saturation region. So, which indicates that the combination of the input voltage, then the device characteristic along with W and L. And, the value of the registrants supply voltage should be such that that device may be in the, it may sometimes it may be in saturation region, sometimes it may be in triode region.

So, anyway so, it is not necessarily true that the device it will be nicely in saturation region by default. So, we have to in fact, verify it. Now, let me consider if the input voltage it is changing with time then what happens.

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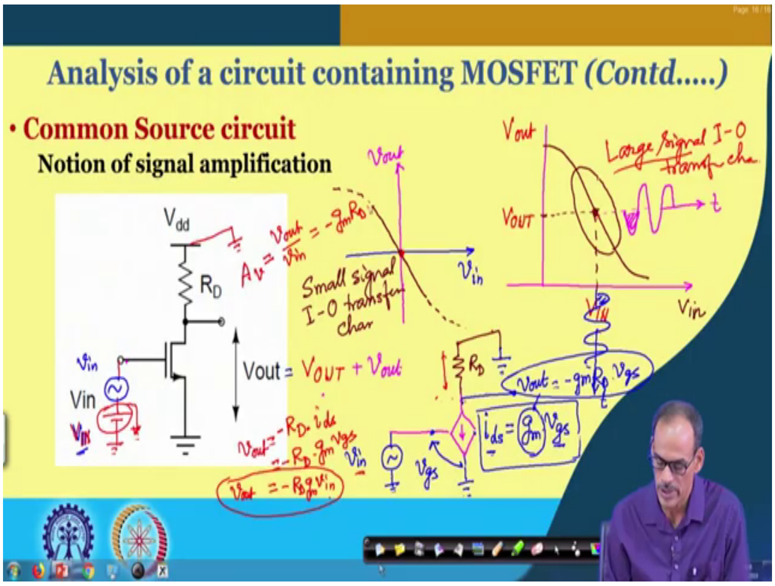

So, in other words if I say that input it is varying, but instead of giving just variation with time slowly. If we are having a situation where the we do have a DC voltage at the input or at the gate on top of that if we are giving a signal. So, you may say that this is V in V capital IN here and the blue part the signal part it is v in and at the output corresponding to this DC voltage we may be getting one DC part. So, this DC part we may call V capital OUT and then on top of that we may be having the small signal or the signal out.

Now, whenever we are talking about say these two basically they are representing the DC part. And, if you are observing the signal here and signal here what we said through the input to output transfer characteristic. So, we said suppose input to output transfer characteristic is like this and so, this is V in which is having DC as well as the small signal part. And here, we do have the V out which is also having DC as well as the small signal part. And, let me assume that the V in it is such that it is making the center point almost at the middle of the linear part. So, the V out part it may be nicely coming there.

So, this is the V capital OUT and this is the V capital IN and then here we are changing this V IN with respect to time. So, if I say this is the time axis with respect to time, this V IN we are changing up and down. So, at the output what we are expecting is so, at the output we are expecting that this will be going down and then up, down and up with respect to time.

So, you may say that this is the small signal input the corresponding effect it is coming here, here. And, as I said that the small signal input to a small signal output that gives us another transfer characteristic. Or in fact, you may say that this part rather this part of the transfer characteristic, if we nicely shape to another graphical representation where x-axis is representing only the small signal part.

And, likewise if the y-axis it is representing small signal output part and then the transfer characteristic curve; input to output transfer characteristic curve it is such that it is going through the origin. Beyond this of course, maybe it is having some significant non-linear part, but as long as it is linear around and the q point the operating point maybe we are happy.

So, this transfer characteristic curve it is referred as small signal. So, small signal input to output transfer characteristic curve. On the other hand this is referred as large signal input to output transfer characteristic curve.

In fact, if you see here this large signal input output transfer characteristic curve it is having the capability to represent the small signal input to output behavior. But, many a times we prefer to use this one assuming this operating point is not changing to simplify the analysis to simplify the circuit behavior and so and so.

So, if you see here the equivalent situation. So, here the DC part if you drop which means that this DC voltage we are making it is AC ground, even this part also we are making it ground and that makes the equivalent circuit which is which is referred as the small signal equivalent circuit.

So, if you see the equivalent circuit for small signal situation, you may say that at the gate we are applying only the small signal part; namely, the small v in part. And at the; so, this V GS now, we will be calling this is small signal v gs. The current here on the other hand whatever we call it is i ds, now it is a small i ds; so, that is equal to it is just g m into v gs. So, which means that this g m it is basically slope of the v gs to i ds characteristic curve and that slope it is basically the important parameter to represent this i ds in terms of the v gs part.

So, if you see the circuit here, it is just if I assume that this part it is remaining constant, then you may say that this relationship it is just linear one. And interestingly of course, rest of the thing it will be linear the particularly the load part which is R D and this is connected to you may say AC ground it is not DC ground, but it is connected to AC ground. Source node anyway it is connected to actual ground and then whatever the voltage it is getting developed here it is small signal v out.

So, if I analyze this circuit, simple simplified circuit where the voltage dependent current source it is represented by this one; so, which means i ds is equal to g m into v gs. So, that gives us the output signal here, which is v out equals to this current is flowing through this resistance. So, that makes g m minus g m into R D into v gs, ok.

Let me rewrite this part it is getting clumsy. So, what we are saying that if I analyze this circuit, we can get small v out equals to R D multiplied by the current i ds, but the current is flowing out of this node and the other side it is connected to ground. So, which means, that I need to put the minus sign here. Because, the drop across this one it is having plus here and then sorry, minus here and then plus here and this side it is connected to ground. So, the voltage here it is minus R D into i ds.

In fact, i ds expression of the i ds it is g m into v gs. And incidentally v gs it is v gs it is same as V in so, we may say that then v out it is. So, you can say that v out equals to minus R D into g m into v in. So, that gives us the gain of the circuit namely, v out by v in equals to minus R D into g m.

So, what is this g m? So, at least we understand that the gain of the circuit namely voltage gain defined by v out by v in equals to minus Gg m into R D. So, let me wipe out this slide and discuss with neat notation.

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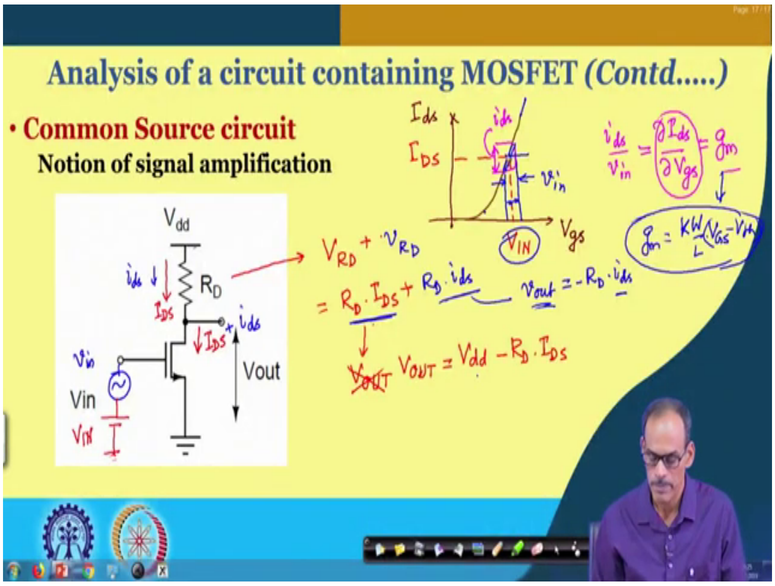

So, what we said is that we are applying a signal here and then we do have a DC voltage and then at the output you are observing the corresponding effect. We do have a DC current I capital DS, in addition to that we do have small signal current i ds. This i ds part it is due to small signal v in and the red part it is capital V capital IN. So, while these two currents are flowing through this register.

So, both i ds and capital I DS; so, this is capital I DS they are flowing through this resistance. So, that makes the drop across this R D is V RD plus small v rd. In fact, if you see here this V RD part; this V RD part it is RD multiplied by capital I DS and the signal part it is on the other hand it is R D into i ds.

And this part, what we said is the DC part of the V OUT rather I should not say exactly DC part, this gives the DC part in fact, I should say the V dd minus this part is the V OUT part. So, I should say I should not be directly writing like this. We say that this gives us V OUT; so, we can say that V OUT is equal to V dd minus this R D into I DS; whereas, this part this part it gives us v out equals to minus R D into i ds.

Note that for signal we consider this is AC ground; so, for signal we do not have this V dd part there. And, it can be shown that as I say that this i d; so, I V part if you see in terms of V gs. So, if you if you consider the I V characteristic; namely, I small ds containing both DC part as well as the small signal part versus V gs containing both DC part as well as the small signal part.

And, the characteristic equation it is let me use this color like this and if I say that V gs or V in part it is a remaining in the almost constant. So, you may say that this is V capital IN and then that gives us the corresponding current here I capital DS. And, with respect to this V IN whenever we change this gs so, may say that with respect to this operating point called operating point.

If we vary then whatever the change we are applying here, let you call v in and the corresponding effect is coming there to the I DS, we call this current it is small i ds. So, from here you may say that i ds by V DS sorry V in is nothing, but the slope of this characteristic curve or this is equal to change in I ds with respect to change in V gs.

In fact, that is what we are defining as g m and this g m if you take the derivative of I ds with respect to V gs. As we have just now we have seen that this g m is equal to K into W by L into V GS minus V th. In fact, we may have different expression; so, the g m is at least this is one nice form of the g m.

So, let us consider one numerical example and try to see what may be the gain. First we will we will find the operating point and then we will find the slope. By the way, the slope of this line of course, it depends on wherever we are considering namely if the center point it is somewhere here, the slope it will be less, if we consider above here probably the slope it will be more and so and so. So, based on the DC voltage or the DC operating point slope may vary, right.

So, first thing is that we need to find the operating point then surrounding that operating point we need to find the corresponding slope. So, as I said that let me try to make an attempt to find gain of an circuits, simple circuit how do I start, yeah.

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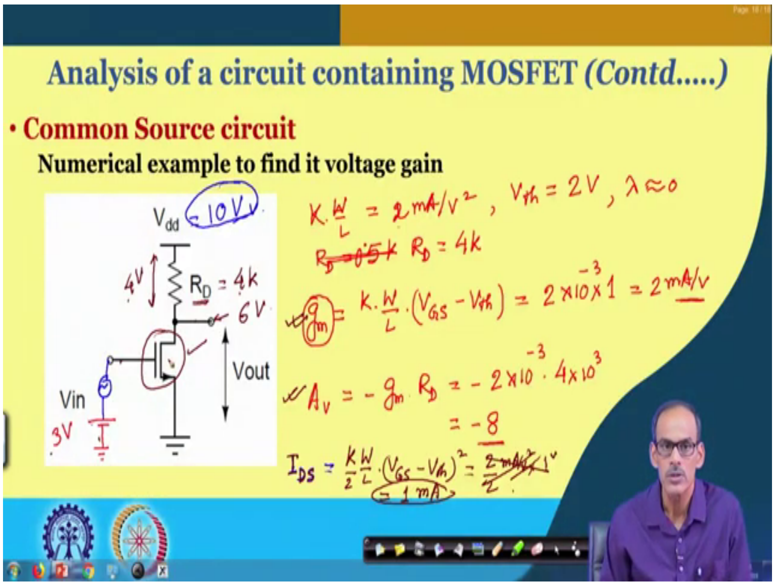

So, this is a 10 volt and let you consider that we are, yeah. So, if you have 10 volt here and then we are applying a signal here maybe this is a 3 volt as we have just now consider to find the operating for the DC condition. So, let it be 3 volt and let you consider K into W by L everything together if I consider this is a maybe 2 milli ampere per volt square and V th. Let you considered 2 volt lambda, we may consider approximately 0, R D let you consider 5 0.5 otherwise the device, no we can consider.

In fact, we may consider R D equals to say may be 4 K. Note that W by L we have considered along with this K and then we are taking this parameter is equal to 2 milli ampere. Earlier this part it was 2 milli ampere and this part it was 10 that is why we are having the device entering into triode region with R D is equal to 4 K.

So, anyway with this we need to find what will be the corresponding g m. So, we may try to see what will be the g m; g m is K into W by L into V in or V GS minus V th. So, what is the value here we do have 2 milli 10 to the power minus 3 and here we do have 1. So, 3 minus 2, 1; so, that is 2 milli ampere per volt. So, this is basically change in current with respect to change in voltage; so, that is why its unit is ampere per volt.

So, the gain voltage gain is what we said it is minus g m into R D and the g m it is already we said we obtained here it is 2 milli and R D equals to 4 K. So, that gives us a gain of 8 with a minus sign. So, yeah; so, that is a gain of the circuit for this operating point. In fact, if you if you of course, you have to say that we need to verify whether the device it will be really in saturation region or not. Probably, we can quickly verify say, if I consider the I DS capital I DS the DC current; so, that is let me use the other color, yeah.

So, I DS equals to K W by L by 2 V GS minus V th square. So, this is what we are having 2 by 2 milli ampere per volt square multiplied by this is 1. So, that gives us 1 volt squared. So, let me let me ignore this part, the unit part. So, what we are getting here it is 2 divided by 2 then this is 1; so, that is basically 1 milli ampere of current. And, once we have this one milli ampere of current flowing through this device and if it is flowing through this 4 K then drop across this 4 K it is 4 volt. So, that makes this voltage equal to 6 volt.

So, we do have 3 volt here DC device and this is 6 volt. So, definitely that ensures the device it is in the saturation region. So, we have picked up appropriate value of the value of the resistance on this voltage, in case if on the other hand if you are making say this is something different. So, for example, if you consider this is 5 volt and then the 5 volt here it will be making this corresponding current it will be very high. In fact, that will be 5 minus 2; this is 3, this 9 milli ampere. If 9 milli ampere has to flow through this 4 K then drop across this resistance it will be much higher than 10 volt.

As a result the device it will be entering into the triode region and hence calculation of the g m following this equation and finding this gain will not be having any meaning, ok. So, later we will see that how to pick up the appropriate value or combination of the voltages and all, yeah. So that is, that brings to the I think end of our main topic.

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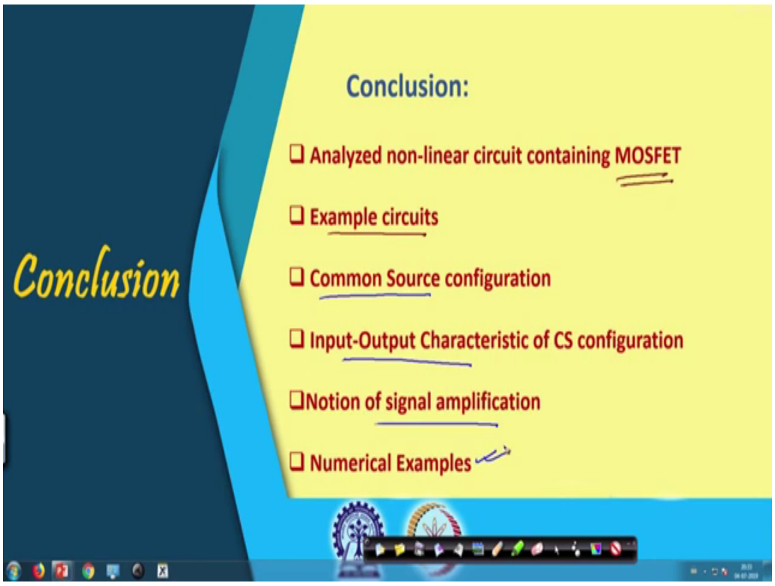

So, what we have covered today it is we have analyzed a non-linear circuit containing MOSFET. So, both we primarily have discussed with the examples having -MOSFET, but also we have considered one circuit containing P-MOSFET.

Then, we have discussed primarily the common source configuration and then also we have seen the input to output transfer characteristic of the circuit. Then, we have seen that this circuit it is able to amplify signal and its gain expression also we have seen. And of course, we have covered we got some time to cover two numerical problems; one is for finding the solution point and namely the DC operating point, other one is to find the gain of the circuit.

Thank you for listening.