Analog Electronic Circuits

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Lecture – 13

Revisiting MOSFET (Contd.)

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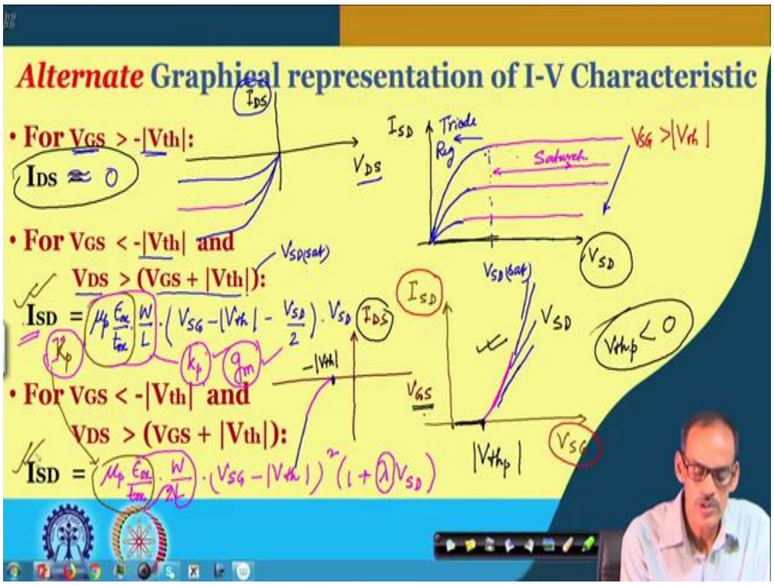

Ok, so after the break so we are back here. So, let me continue the graphical interpretation of the I-V characteristic and as an exercise I have asked you to make rewrite this expression of the current. As I said that if V_{SG} it is less than a threshold voltage or practical purposes you may say that this is equal to 0.

On the other hand if VSG is higher than V_{th} and V_{SD} it is less than $(V_{SG} - |V_{th}|)$. In fact, this is nothing but the pinch off condition we are avoiding and in this case the current is it is $\frac{\mu_p \varepsilon_{ox}}{t_{ox}} \cdot \frac{W}{L} \cdot (V_{SG} - |V_{th}| - \frac{V_{SD}}{2}) \cdot V_{SD}$. And we will see that as you have discussed for n-MOSFET this is nothing but referred as linear region of operation or it is also referred as triode region of operation.

On the other hand if the pinch off it is happening namely if V_{SD} it is more than $V_{SG} – V_{th}$ or so, in that case I must say that the pinch off already happened and then the x the current it is having hardly any dependency on V_{DS}. So, and this is the k part and then $\frac{W}{L}$ into we do have 2 here and then $(V_{SG} - V_{th})^2(1 + \lambda V_{SD})$.

So, let us see what the graphical interpretation of this is, and to start with let me let you consider say for a given value of V_{SG} let you observe I_{SD} as function of V_{SD}. So, initially if you see a V_{SD} it is less than this voltage which is referred as $V_{SD(sat)}$. So, till that point we may say that it is parabolic in nature or second order kind of things, but then instead of really going this parabola beyond that. So, this is the point where $V_{SD} = V_{SD(sat)}$ and beyond that point the current do get saturates. So, the current remains constant and whatever the small slope it may be contributed to this lambda called channel length modulation.

So, this portion we call so beyond this point it is called the saturation region and this region it is from here to here it is missing triode region. And so this is we obtain for a given value of V_{GS} or rather V_{SG} higher than V_{th} magnitude. And so if you are decreasing the V_{SG} will be getting similar kind of characteristic. But of course, the corresponding pinch off it will happen a different point, because the pinch of course it depends on and the corresponding $V_{SD(sat)}$ so it enters to the saturation at different voltage and so and so.

So, if you decrease the V_{SD} it will be going like this; so, V_{SG} if you are decreasing and if it is going towards V_{th} then it enters to the cutoff region. So, in here we do have the cutoff region, so the cutoff region it is coinciding with V_{SD}-axis. And on the other hand if you are observing the corresponding current as function of V_{SG} as function of I_S sorry I_{SD} as function of V_{SG}.

So, here what you can see, it starts with rather saturation first. So it of course, initially it will be have been cutoff then it is having saturation. In the saturation region, it is having square dependency and then it goes to the linear or triode region and below this of course we do have the cutoff region.

So, that is the different range of the; so, this is of course for a given value of V_{SD} and if you change the V_{SD} two different values, then for smaller V_{SD} it may enter into triode region before, then this point or maybe later depending on the value of the V_{SD}. So, this is what the graphical representation. So, it is very similar as I said except of course, the instead of I_{DS} we call I_{SD} and instead of V_{GS} we call V_{SG} and so and so.

There is an alternative way of representing this. So, I should say people call it is alternate representation graphical representation of the same thing, what is the difference there it is instead of plotting this I_{SD} verses V_{SD}. If you try to plot say I_{SD} verses, rather I_{DS} versus V_{DS} to maintain the consistency with the n-MOS. In that case the curve it will be I-V characteristic curve it will be getting shifted to the third quadrant. So, this will be the triode region and then it will be entering to the saturation region.

So, for different values of, different values of the V_{GS} or V_{SD} you will be having different kind of different I-V characteristic plot. So, of course, this is for we are discussing about p-MOS. So, for p-MOS you may say that whenever we are observing we are claiming that or we are trying to pertain that I_{DS} is the +ve the actual direction polarity of the current is from source to drain. As a result it is having you may say –ve direction current.

So same thing for the voltage also, so if you say that for actual operation source is at higher potential then drain which means that V_{DS} is actually –ve. So, same thing you can it can be also discussed about the I_{DS} versus V_{GS}. So, if you plot I_{DS} versus V_{GS} instead of V_{SG} as you can guess that the corresponding I-V characteristic plot it will be it starts with beyond threshold, it starts with the saturation region and then it enters to the linear region.

And this voltage of course, up to this voltage the current is 0 and if you see that if you consider V_{GS} is your parameter, then this is the point where the device starts working or you may call this is the threshold. And, since it is coming on the –ve side so, you may say that the threshold here it is now $-V_{th}$. So, that is why whenever you are talking about p-MOS transistor, we may say that the actual threshold voltage is actually –ve.

So, V_{th} in other words for p-MOS device V_{th} it is –ve and to avoid this confusion in this plot and this plot to get the correct interpretation, we prefer to use the mod here V_{thp}. So, if say V_{th} is given to us it is a –ve and if you take the mod then we will be getting on the +ve.

So, in this representation the first representation where we are plotting I_{SD} verses V_{SD}, we know that the threshold voltage it will be right side of the origin and hence it is +ve. On the other hand some people as I said are trying to plot I_{DS} versus V_{GS} for p-MOS transistor, there of course the threshold point it will be lying on the left side of the origin and hence it is actually –ve, ok.

So, that is about the representation graphical representation of the I-V characteristic of the MOS transistor. It is better to consider this convention rather than this one, because of the similarity of the I-V characteristic with respect to npn, but as I said that we need to be careful about the subscript part, the direction of the voltage and the direction of the current.

So, let us go to some of the numerical problems, probably when you consider the circuit particularly on an electronic analog electronic circuit where the device may be or really existing or maybe the technologies already decided. So, in that case what we can say that whether you consider this equation or this equation.

The parameter there it is we can say that this portion it is constant called K and similar to of course the n-MOS device and here since it is mobility of the p-type device. So, or I should say mobility of the holes is involved here and this K it will be different from K for n-MOS transistor, as a result we may use different value of K and we prefer to use subscript p.

So, this is called transconductance parameter and then if you already have so this is also k_p trans conductance parameter and in case if the device it is already got implemented then W and L is also decided. So, in that case the whole thing it can be considered as constant. So, you may say that the whole thing either this one or excluding this two part, this factor is given to us. So, this is also referred as another constant k with a k_p excluding this two. So, this k_p it is referred as transconductance factor.

So, this is parameter and this is factor. So, that you need to be careful and of course later on we will also see that some another parameter small signal parameter called transconductance g_m. So, this transconductance part it is utilized in multiple places please do not get confused, one is transconductor parameter K and transconductance factor k and then transconductance of the device.

So, this one we will see it later. So, in case if we are dealing with a circuit probably the value of this k or this K it will be given to us along with maybe W and L or maybe you have two different decide what will be W and L, and maybe for given value of V_{SG}, V_{SD} we may have to find the current and so and so. And also maybe you have to see whether the device it is in triode region or it is in saturation region based on that we may use this equation or this equation, ok.

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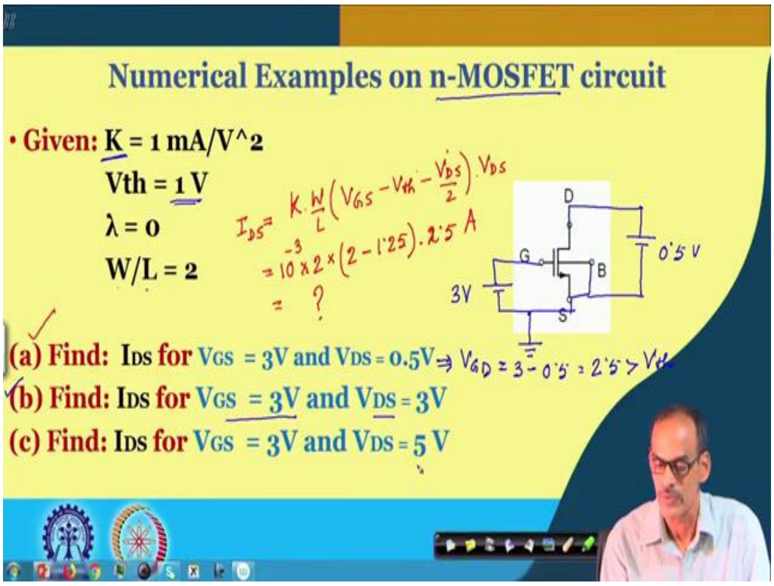

So, let us go to some as I said let us move to some numerical example. So, let us see what we have this numerical example here. So this is of course numerical example using n-MOS transistor. So, we do have n-MOSFET and the value of key transconductance parameter it is given to us 1 mA/V^2. A threshold voltage of the n-MOS transistor it is given 1 V, λ you can; in this example you consider it is very small which means that channel length modulation we are almost ignoring, $\frac{W}{L}$ the aspect ratio of the channel it is given to us as 2.

Now, we do have three parts, so let us let you consider part-(a) and the V_{GS} is given to us is 3 V. We assume that this is connected to source and without loss of generality let us assume that this is connected to ground. So, we do have 3 V here and then we do have different values of the V_{DS} and we need to find what will be the corresponding I_{DS} current.

So, we do have V_{DS}. So, if you see here this is 0.5 and V_{GS} is 3 V threshold voltage is 1. So of course, the device it is on V_{GS} is more than V_{th}, but you have to also see whether the pinch off it is happening or not by considering V_{GD}. So, in this case V_{GD} if you see here so V_{GD} = 2.5.

So, 3 – 0.5; so, that is 2.5 which is of course higher than V_{th}, which means that channel is existing to the drain end also in other words the pinch off is not happening. So, we have to use the equation the corresponding equation of the I_{DS}. So, let me use this you may recall this I_{DS} expression that $\frac{KW}{L}$ $(V_{GS} - V_{th} - \frac{V_{DS}}{2}) \times V_{DS}$.

So what we have here it is 1 m that means 10^{-3} this is into 2, then we do have 3 –1, so that is we do have 2 here and $V_{DS} = \frac{2.5}{2}$, yeah. So, this is – 1.25) × V_{DS} so that is 2.5; so, this much of ampere so you can find what will be the corresponding value. So, only thing is as I said that you need to be careful that the device whether I have to consider this triode region or we have to consider in the saturation region, so this is now done.

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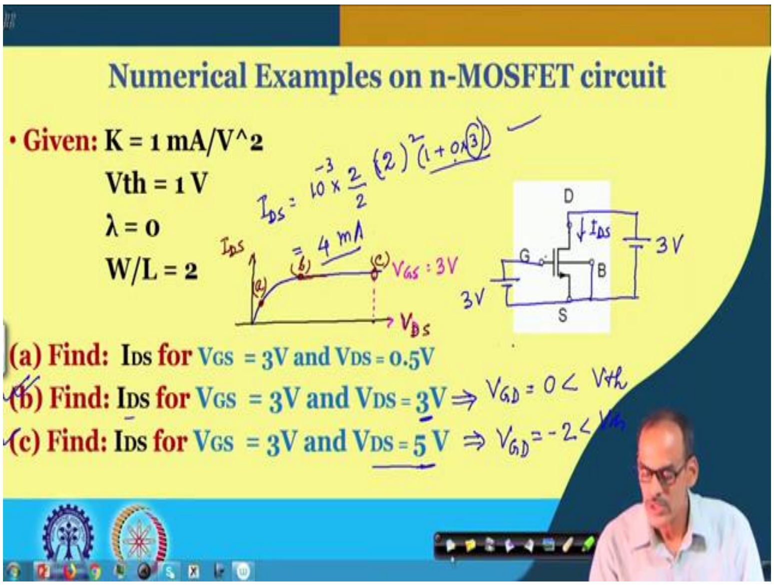

Now, let us look into the next part-(b) so here V_{GS} we are keeping same, but then V_{DS} we are changing to 3 V. So, what we have here it is to consider this part we do have 3 V here, body is connected with this and then we do have here also we do have 3 V. So, as you can see here V_{GS} is more than V_{th} of course, the device is on and however V_{DS} since it is equal to V_{GS}. So, drop across this one it is just 0 voltage.

So, for this case V_{GD} = 0 V, so that means the pinch off is happening because it is less than threshold voltage. So, the equation will be using for this case it is to find the I_{DS} current we need to use this I_{DS} equals to and this K which is $10^{-3} \times \frac{W}{L}$ which is 2. Then $V_{GS} - V_{th}$ so that is again 3 – 1, so that is also 2. So, that square divided by 2 into $(1 + \lambda V_{DS})$. So, that is $\lambda = 0$ into this 3. So, this part becomes 1 and that is how we are getting equal to 4 mA.

So, the current here it is actually 4 mA current. So, likewise you can find this one, here it is very straightforward the device the pinch off the V_{DS} is further increase compared to this one. So, the in fact V_{GD} if you see here, now it is –ve rather; so, definitely this is the pinch off is happening. And again, I should use the same equation, only difference is that this V_{DS} instead of 3, now I should use 5. But anyway we do have this is equal to 0, so here also we are getting I_{DS} = 4 mA.

So, pictorially you may recall that different region of operation. So, we do have different region of operation. In first part we are so this is for all cases we do have the same V_{GS}, V_{GS} = 3 V, but then we do have different V_{DS}. So, for one case we do have 5 V here, so this is V_{DS}; so, this is V_{DS}-axis, this is I_{DS}-axis.

So, for case-(c), we are here and for case-(b), they are also we are in the saturation region and on the other hand for case-(a), we are somewhere here. So, (a) is here then (b) is here and then (c) is here. So, for this case since λ is very small; so, we are getting same level of current namely 4 mA here the current it was less. So, that is how we can solve numerical problems probably you can try out now one numerical problem on p-MOS transistor.

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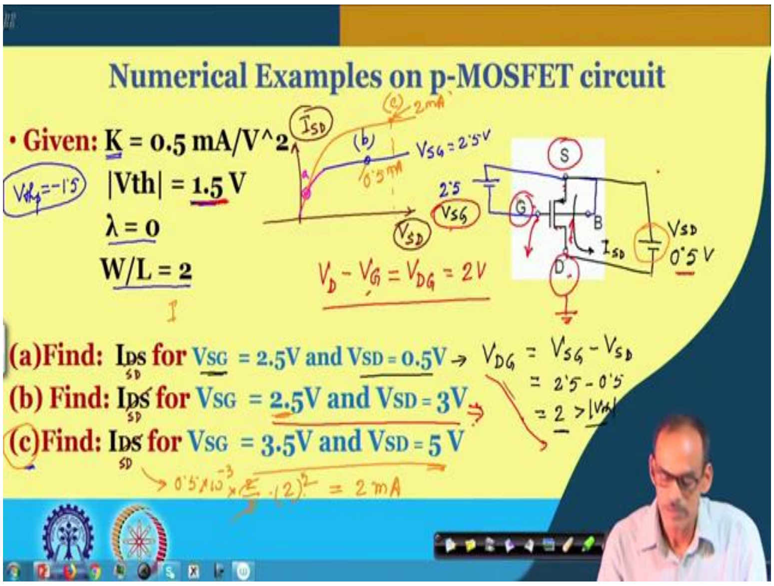

It is similar but of course, I have changed the parameter. So, what are the changes we do have here, the V_{th}, $|V_{th}|$ it is instead of 1 we are considering 1.5. In fact, you may recall V_{thp} sometimes if it is given directly it may be given this V_{thp} is –1.5 ok, it is I should say it is same.

So, here also we consider $\lambda = 0$, $\frac{W}{L}$ the aspect ratio = 2 and the transconductance parameter K it is 0.5 instead of 1.5 mA/V^2. So, I will be giving just hint probably you can work it out V_{SG}, so whatever the difference we do have compared to the previous case now we do have the V_{SG} here. So, this is for case-(a) and (b) we do have 2.5 and then of course body is connected here, and then V_{SD} on the other hand we do have V_{SD} this is for first case it is 0.5 V.

And so now, if you see whether in this case whether the device it is in triode region or not what we have to do. Of course, the V_{SG} it is 2.5 which is higher than the threshold voltage, so the channel is on at the source end. Now, we have to find what will be the condition of the V_{DG}.

So, in this case V_{DG}, so V_{DG} it is drain voltage with respect to the gate. So, what we have here it is the common is source. So, you may write this is V_{SD} and this is V_{SG} all right and so you can write this is as $V_{SG} – V_{SD}$. So, this is equal to we do have 2.5 – 0.5 = 2, which is of course higher than magnitude of this threshold. Which means that, so here also we do have the channel so that means the pinch off yet to happen and as a result we may say that this is we have to use the triode region equation and accordingly you can find the corresponding current here the I_{SD}, right.

So, please do not get confused about the different polarities and all the simplest way of looking into the device is my suggestion will be like this. If you see here now we know that gate will be at lower potential with respect to source and to have the channel and not only the gate should be at lower potential than source. But of course, with at least with this much of margin to have the channel existing and it is valid for the drain region also.

So, in other words the gate should be at lower potential than the drain to have the channel and the difference should be at least the V_{th}. Now if you see here this is the common terminal source with respect to that the voltage here it is 2.5 lower, whereas for this case it is only 0.5 lower. Which means that the gate voltage and if I compare gate voltage and drain voltage, gate voltage is definitely lower than drain voltage, because this is smaller and in fact the difference here it is 2 V.

So, I should say gate voltage $V_G – V_D$; so, sorry I will take it to the other way $V_D – V_G$. So, that is what we call V_{DG} so that is 2 V. So, as long as this is at lower potential and this is at higher potential and the difference is at least this much, then you can say the channel is existing; that means, the device yet to enter into saturation still it is in triode region.

So, that is how you can look into this one. In fact, instead of considering source as the reference, in practical circuit will be having rather reference it will be towards the drain and we may be having some circuit here. So, instead of trying to compare this V_{SG} and V_{SD} and following this one we may prefer that individual node voltage gate voltage and drain voltage with respect to the common voltage.

So, instead of this formula probably this is what it will be more convenient and you can find whether drain is at higher potential than the gate by a margin of threshold voltage. So, that may be a better way to judge whether the device it is already having pinch off or whether it is in triode region. Probably you can work out for this case and it is of course the actual solution is the device it is already in saturation.

So, in this case the if you recall the I_{SD} ok, sorry I should write here I_{SD} instead of I_{DS}, so that you will get +ve entity here. So, anyway I_{SD} versus if you plot V_{SD}. So, since we are taking care of the subscript, so that the I-V characteristics should remain in in the in the first quadrant.

So, we do have the saturation region here and then we do have the triode region here and for case-(a) the device it is somewhere here, so this is the case-(a). Whereas, for case-(b) it is the device it is it enters into saturation region and this is for V_{SG} = 2.5 V and probably you can find what will be the corresponding current.

On the other hand for case c of course, the V_{GS} or V_{SG} it is different instead of 2.5 now it is we do have 3.5 rather. So, the corresponding I-V characteristic it will be different like this and however this V_{SD} it is sufficiently high probably it is somewhere here, so the case c it is here.

So, then you can of course, the device it is already in saturation you can find the corresponding current. In fact, if you see here quickly the I_{SD} for this case or this case maybe we consider this case, here it is 0.5×10^{-3} and then we do have $\frac{W}{L}$ is 2 then we do have another 2 here and then V_{SG} is 3.5 – 1.5 that is 2^2 and $(1 + \lambda V_{DS}) = 1$.

So, what we are getting here it is this two are getting cancelled we do have 4 here and then we do have 0.5, so that gives us 2 mA. This is the case for this one, on the other hand for this case this part instead of 2 it will be 1. So, there you will get for this case you will be getting 0.5 mA. So, this is you should say 0.5 mA and this is 2 mA and likewise.

So, if you see here we are applying the terminal voltage directly, may not be the case always like this. So, in case if it is rather if you are moving towards more practical circuit instead of giving independent supply at the drain and source we may be having rather different situation.

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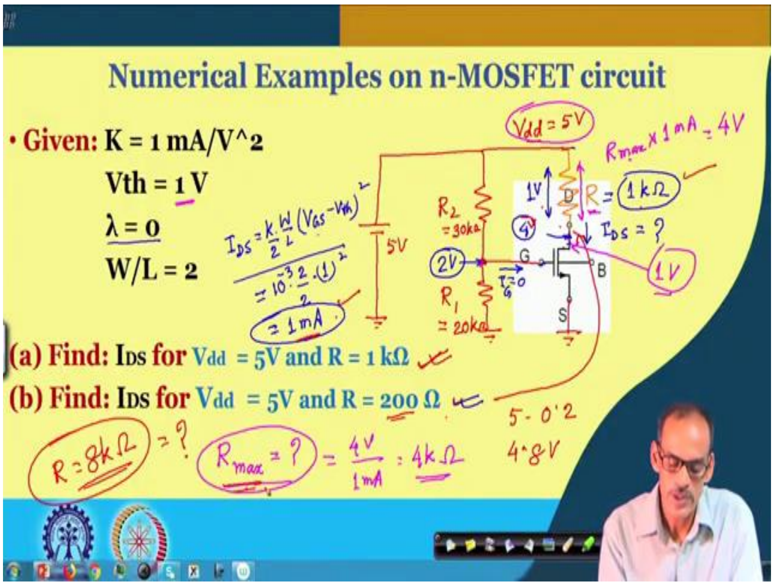

So, let me frame this problem for you, so we may be having a so this is using n-MOS. Of course, so let you consider we do have a supply voltage, but then at the drain we do have a resistance and this is called R and let you also have potential divider to generate the gate voltage. So, we do have a potential divider here and this is say connected to ground and let you consider that this is may be may be R_1 and this is R_2 and let you consider this is this is getting a DC voltage from a battery say 5 V.

So, we call this is V_{dd} = 5 V. Why is it V_{dd}, because this voltage it is not directly coming to the drain, it is final it is going to the drain, but through some other element. So, the voltage here it is referred as V_d to distinguish that V_d and this voltage normally it is used as dd's. So, we call this is V_{dd} and this is 5 V and for this case let me consider that this may be say 2 k or 20 k say, 20 kΩ and this is let you consider 30 kΩ.

So, that makes this potential divider making this voltage equal to so, 5 V it is getting divided by these two resistors and the voltage coming here it is 2 V. From the potential divider you can get and in fact since the current to the gate it is 0. So, even after connecting this gate to this node the voltage remains 2 V unlike V_{GD}. So, dc wise at least it is not drawing any current.

So, the so that makes the voltage here directly coming from this 2 and so if this is 5 V and then if this is a 1 kΩ, can you find what will be the I_{DS}. So, how do you proceed, first of all for simplicity suggestion will be first you assume that device it is in saturation region, because the expression of the current in that saturation current it is relatively simple.

So, we considered I_{DS} = $\frac{K\times W}{L}$ and 2 also and then we consider $(V_{GS} - V_{th})^2$, ok. So, we assume that λ is approximately 0; so, we can ignore the I_{VDS} dependency. So, this makes of course which we are assuming this one and end of it we also have to verify. In case if the device it is not really in this region saturation region, then you have to use the triode region equation and then you have to solve the second order equation to find the V_{DS}.

So, let you consider say this case first and probably in this case the device it is in saturation region. So, the voltage here it is 2 V. So, this part it is 1 and so here whatever the parameters are given here it is K = 10^{-3} and $\frac{W}{L}$ it is 2 and then we do have another 2 here and then we do have this is 1^2. So, that gives us 1 mA current.

So, we do have 1 mA of current and we do have 1 K resistance here. So, if this current is 1 mA then drop across this one it is only 1 K × 1 m. So, this is 1 V. So, we have 5 V here the voltage coming here it is 4 V. So, the voltage here it is 4 V and if it is compared. Now we do have 2 V here we do have 4 V here. So, if you see the gate voltage and says source the drain voltage difference of course, gate voltage is lower than the drain voltage.

As a result we already have the pinch off happening which means that the device is in saturation. So, then our initial assumption is correct. So, then we are correctly getting this 1 mA of current. Now let us see the other case, so instead of this one let you consider this case and again let you start from this assumption, that device it is in saturation and if that is true then the current here it will be oh sorry we already have considered this case sorry. We already have considered this 1 mA and if it is 1 K then the voltage drop here if this is 1 V and then we do have 4 V here. So, the device in saturation in fact the device is here as well as here it is in saturation.

In this case of course, the drop here it will be less rather it will be only 200 mV. So, for this case the voltage at this point it is 5 – 0.2. So, that is rather 4.8 V and anyway the device is remaining in saturation. Next part it is that can you find the value of this R or rather maximum value of R. So, that the device it is just in saturation.

So, to find that you need to know what will be the voltage require here. So, that the pinch off it is just happening, if this is 2 V and threshold voltage is 1. So, the pinch off it will just happen when this voltage it is 1 V. So, to find this one I should start with this 1 V and then if the current here it is 1 mA for this V_{GS}, if the device is remaining saturation. So of course, at the verge of that saturation the current is also 1 mA assuming $\lambda = 0$.

So, the drop across this 1 for this R_{max}; so, R_{max} × this 1 mA should be equal to 5 V – this 1 V so that is 4 V. So, that gives us $R_{max} = \frac{4\ \text{V}}{1\ \text{mA}}$ so that is 4 k. So, this R it can go as high as 4 k without any problem, but then if this resistance is more than this one. So, let us consider this is 8 k. So, then what happens.

Probably you can find what will happen if R = 8 kΩ then what happens, what will be the current. Whether the current will increase or decrease of course, the device would it will enter into triode region. So, probably later on we will see what will happen. But for most of the analog circuit we prefer to keep the device in saturation region, probably for analog circuit then we will not be really venturing out to increase this R beyond this value, in case if you are increasing the diode the device it will enter in triode region.

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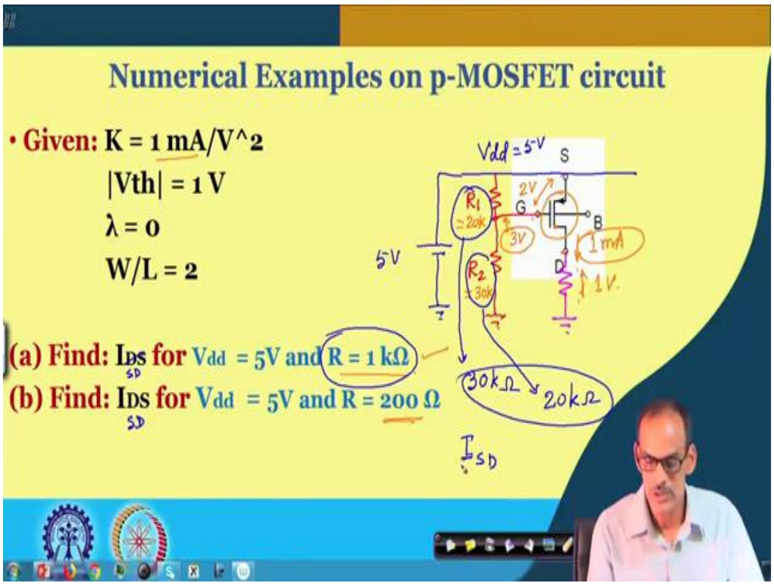

So, let me at least give one numerical problem similar to the previous case and however let me use different of course the appropriate bias condition. So, we do have the V_{dd} here V_{dd} we consider this is 5 V. So, that is getting generated by a potential say 5 V with respect to ground and then here we do have the bias circuit namely, the resistance connected to the drain and finally it will be going to the same ground. And here we can probably we can keep potential divider like this and this potential divider is providing a voltage for the gate so here also the current is 0. So, whatever this R_1 and R_2 is ratio based on that we can find what will be the voltage here.

So, that will set the, whatever gate voltage or V_{SG} and then for different conditions here, we can find know whether the device it is in saturation or not. So, for a similar situation let me create the similar situation here also. So, let we assume that this is say 20 k and this is saying a 30 k. So, the voltage here it is 3 V. So, that makes this voltage V_{SG} = 2 V, it is similar to the previous case where V_{GS} it was 2 V and the parameter here it is given similar.

So, we can say that if I assume the device it is in saturation, the current flow here it will be with the same calculation it will be 1 mA. So, if I consider first case then of course, the drop here it will be 1 V. So, the voltage here it is 1 V and the voltage here it is 3 V. So, that makes the gate voltage 3 V and this is a1 volt. So that means towards the drain we do not have the channel. That means, the channel the pinch off already happened which means that device it is in saturation region. So, then that assumption is correct and hence the corresponding current it will be 1 mA.

So of course, if the resistance is smaller definitely this drop it will be smaller. So, that makes this device still I mean, rather comfortably remaining in saturation region. So now, let me change this problem slightly different one. If I change this say the this resistance to say 30 k and this resistance to 20 k and then for this case if it is 1 kΩ, can you find what will be the corresponding I_{SD} current.

So, this is I should write I_{SD}, so probably you can find for this case. If R = 1 k you can find what will be the I_{SD}, and check whether the of course, procedure it will be same. You can start with the assumption the device it is in saturation and then you can verify it. I think that is all we need to cover related to device.

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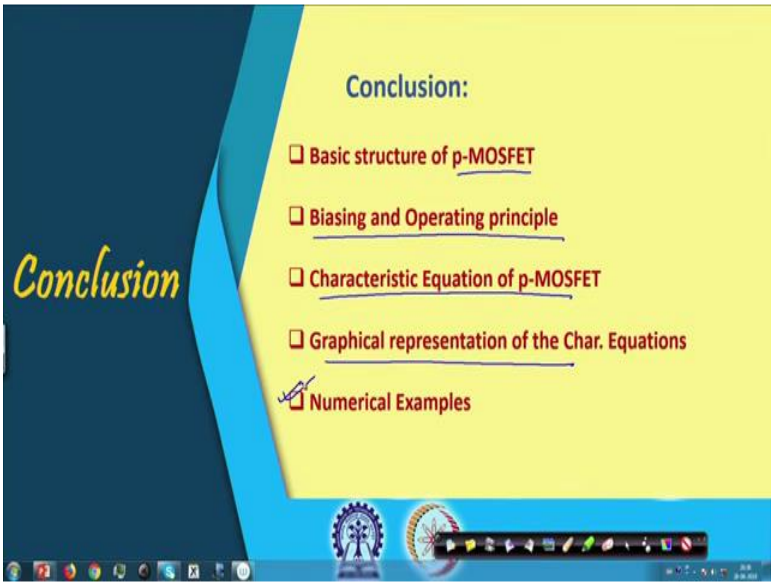

So, what are the things we have covered? So, far the basic structure of the and the p-MOS and we have compared with a MOS transistor, then biasing and operating principle of the MOSFET; p-MOSFET, characteristic equation, I-V characteristic equation of the mass transistor, graphical representation of the characteristic equation and some of the numerical examples. Simple numerical examples to find the current under certain bias conditions. So, this ends to our prerequisite and from the next module we will be directly going to analog electronics in detail, we will start with a simple circuit that is all.