Basic Electronics

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Module: 3 Field Effect Transistors
Lecture-6
Small signal model of MOSFET – Part 2

In the last class we discussed about the small signal analysis of the MOSFET amplifier and we were finding out the important parameters of the MOSFET amplifier using the feedback biasing scheme. The drain is having a feedback resistance to the gate and we saw how the input impedance, output impedance and voltage gain could be found out using the small signal model. Continuing with that let us today proceed to find out these parameters for another type of biasing scheme which is a very popular and important biasing scheme known as voltage divider biasing scheme. Using the voltage divider biasing scheme for the enhancement type MOSFET amplifier we will try to find out these parameters. The circuit using the voltage divider biasing scheme has two resistances R_1 and R_2 as shown in this figure. They are connected to gate terminal we have the V_{DD} as the biasing voltage, the drain resistance is R_D and the source is having this source resistance R_S as well as there is an emitter bypass capacitor C_S.

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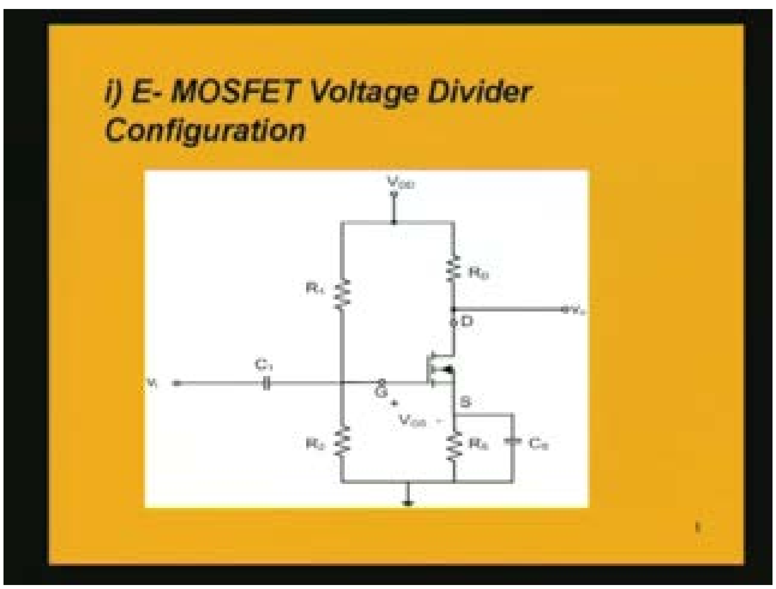

C_1 is a coupling capacitor and in fact there can also be a coupling capacitor in this output side although we are not showing. This voltage divider biasing scheme as we have drawn here is a popular biasing scheme which we were earlier using in transistors using BJT. In order to find out the AC equivalent circuit we know the steps to be taken. One is that we must make the DC bias zero. As we are only concerned with the AC condition, the DC voltages which are present must be made zero or they are grounded. Another step is that the capacitances which are used for blocking the DC component will be assumed to have short circuited part because their capacitance values are chosen in such a way that we can very well assume them to have a short circuited part. All the capacitances will have a short circuited part. As there are short circuited parts they may bypass some of the resistances, like here as the emitter is having a bypass capacitor C_S when it is having a short circuited part, this R_S will be avoided or it will be bypassed. That means the source will be grounded and this is a common source configuration as we are continuing with common source amplifier.

Let us proceed to find out the AC equivalent circuit and we will plug in the small signal model for the device. The MOSFET device will have its small signal equivalent circuit and that will be incorporated instead of this physical device. Proceeding in that manner we have this AC equivalent circuit. It is having the small signal model as represented by this part. This is nothing but the small signal model of the MOSFET device.

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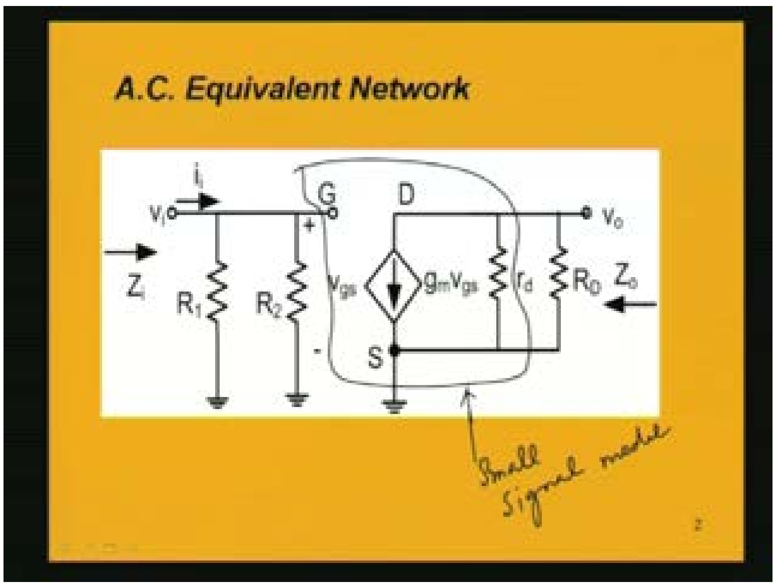

We are using enhancement type of MOSFET and external to this small signal the other components are coming from the equivalent circuit. That is we are having the R_1 and R_2 resistances. As V_{DD} will be grounded we will have a parallel combination of R_1 and R_2. That is shown here. We that the gate terminal is having a parallel resistance combination to ground which are formed by R_1 and R_2 and R_D is the drain resistance which will be there and this resistance R_S will be bypassed by this emitter bypass capacitor which will be simply shorted to ground in AC condition, so that will be avoided. That is the reason we do not see here R_S in the circuit.

In order to find out the input impedance, output impedance and voltage gain, these three quantities we are finding out, and mind it we are not having the source and the load resistance. It is a simple circuit but we can add on the source and load resistance also in the circuit and do the analysis; that is not a difficult one. This v_{gs} is gate to source voltage, the input voltage is v_i, input current is i_i and the output current is i_o towards the device. Z_O is the output impedance which is obtained by looking into the amplifier from this output terminals. Following the usual manner, from the first principle we will find out the input impedance. What is the input impedance? It is the ratio between the input voltage and the input current, v_i by i_i is Z_i. What is v_i? v_i we have the input voltage. i_i we have to find out. Basically what we are going to find out is the ratio between v_i and i_i. Let us express the v_i.

What is this voltage? At this terminal between gate and source or between gate and ground this is the voltage v_i. This is the node voltage v_i. v_i is the current flowing through R_2 multiplied by R_2. That is the voltage. A part of this current i_i flows through this R_1 and another part flows through R_2 and let us name the part which flows through R_2 as i_{i2}; this is i_{i1}.

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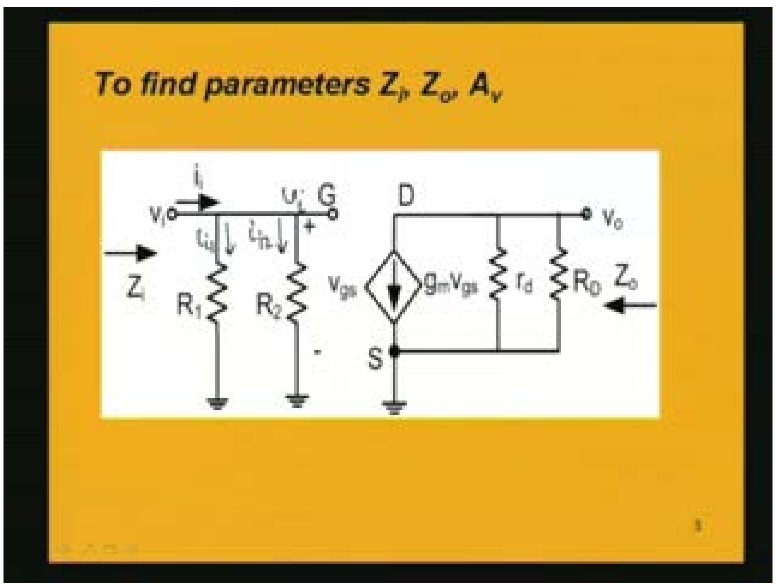

If we want to find out v_i we can write it as i_{i1} into R_2. This is the voltage i_{i1}multiplied by the resistance divided by i_i. Let us express this i_{i1} in terms of i_i. Current division is taking place. So what will be the current flowing through this resistance R_2? That is nothing but i_i into R_1 by R_1 plus R_2. i_i into R_1 by R_1 plus R_2 is the current flowing through the resistance R_2 multiplied by R_2 divided by i_i. This i_i and this i_i cancel out. What we have now is R_1 into R_2 by R_1 plus R_2 which is nothing but the parallel equivalent between the two resistances R_1 and R_2.

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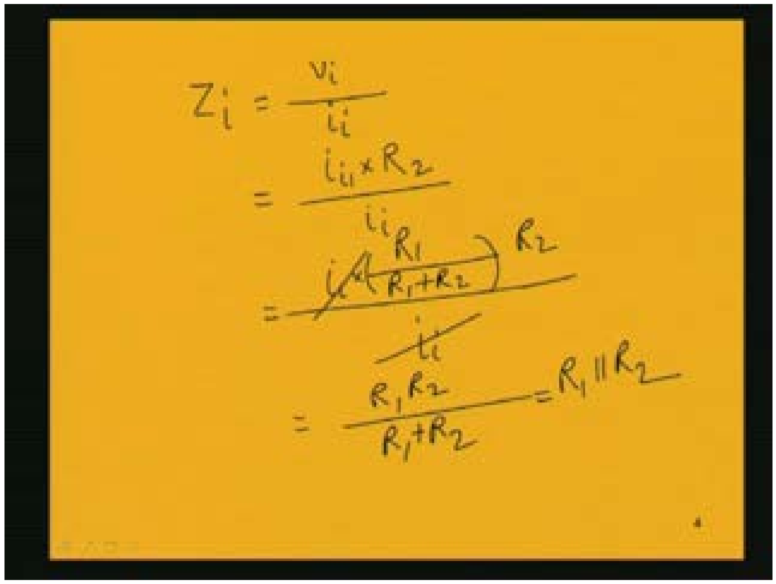

This is as simple as that. So input impedance Z_i is equal to v_i by i_i which is equal to R_1 parallel R_2.

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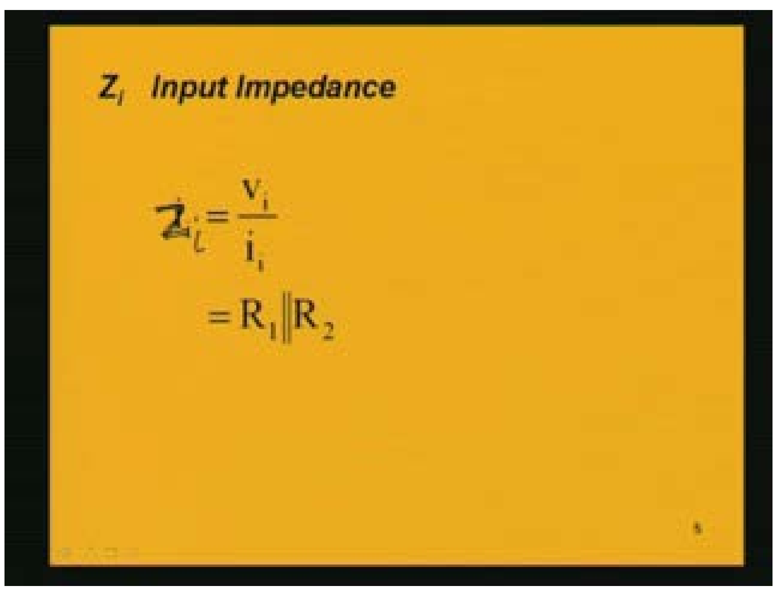

We have found out that and it is very obvious from the circuit also. By looking into the circuit from the input side, the input impedance is nothing but the parallel combination of this two. What will be the output impedance? That can be found out by making the input voltage zero and finding out from the output side. If we make this input voltage v_i zero, immediate consequence is that this current source g_m into v_{gs}, which is nothing but g_m into v_i since v_{gs} is equal to v_i, that is zero. This is like open circuit. Between the drain and source we have an open circuit part. There is no influence from the output on the input. This circuit is totally isolated because it is open circuit.

The consequence of making the input voltage zero for finding out the output impedance is that we can draw the circuit it will have between the drain and the source. Source is here, drain is here. Whatever current source was there, g_m v_{gs} that will be zero and we are having the resistances. These resistances are small r small d and capital R and capital D. So Z_O is found out by looking into the output circuit from the output terminal.

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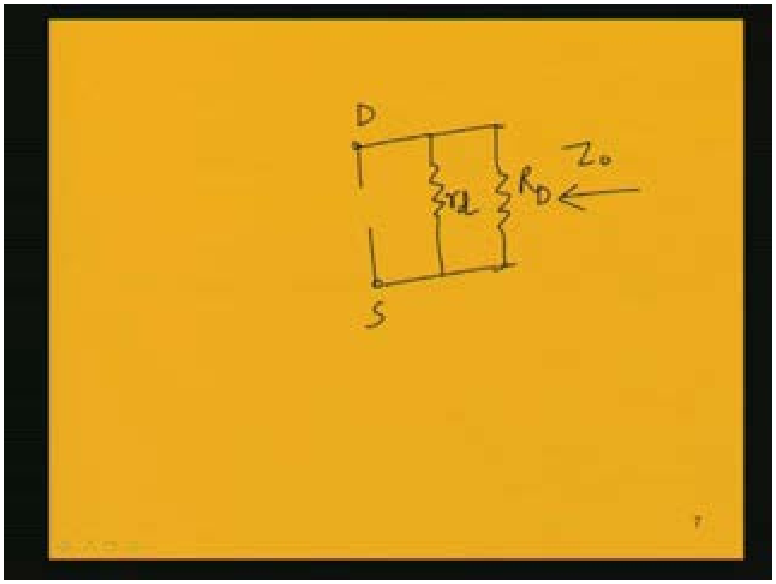

This will be nothing but the parallel combination between these two resistances. So that gives us the output impedance Z_O is equal to small r_d parallel capital R_D. One step further approximation can be done if we make an assumption. What assumption? The assumption is that our small r_d if it is at least equal to or greater than 10 times of capital R_D then we can very well approximate this parallel equivalent small r_d parallel capital R_D to equal to capital R_D. Because we have two resistances one is high and one is low then the equivalent will approach the lower value. We have the output impedance almost equal to capital R capital D that is the drain resistance. If this thumb rule satisfies that is if the condition of small r is very, very greater, at least 10 times or even more; minimum is 10 times or it may be 10 times more than the value of capital R_D, then we get that output impedance equal to capital R capital D.

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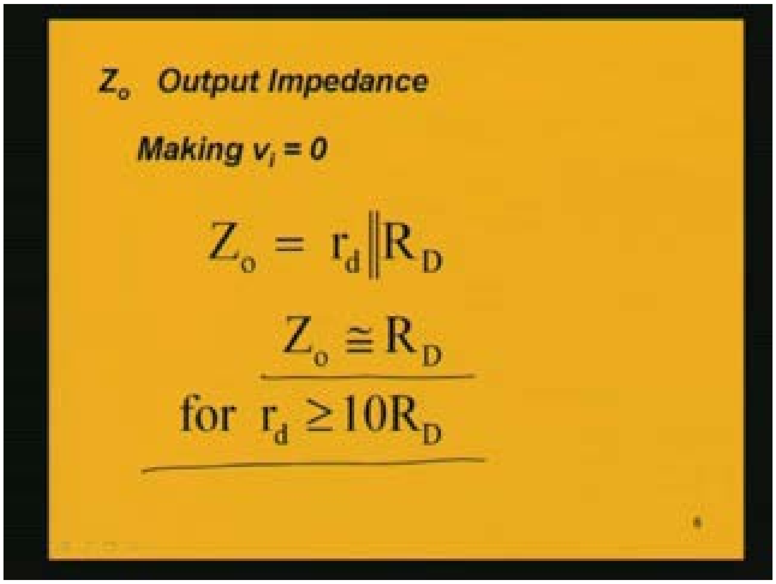

This is not very difficult to achieve because the small r_d value is quite high value. It is evident from the drain characteristic, voltage ampere characteristic between the drain current and the drain to source voltage that the drain current is almost horizontal with the drain to source voltage in the saturation region and it signifies that it has a very high value. It is often true that it is 10 times or more than the drain resistance. Let us find out voltage gain. In order to find out the voltage gain we know that the voltage gain is equal to the ratio between the output voltage and input voltage. That gives us the ratio between v_o and v_i. v_i is nothing but v_{gs}. So replacing this v_i by v_{gs}, we get voltage gain equal to v_o by v_{gs}.

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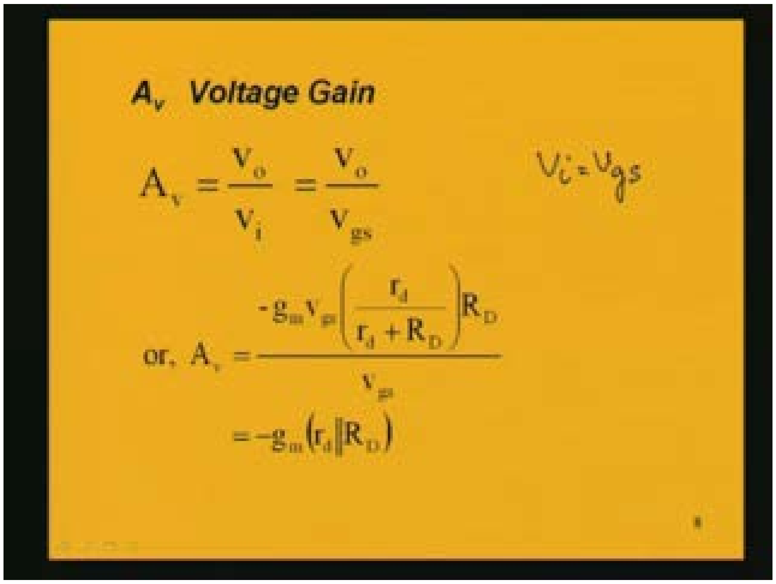

If we can write v_o in some way related to v_{gs} then we can cancel out. We look into this circuit again. We need to find out what is the output voltage? We look into the current source. The current source is the current between the drain and the source which is g_m into v_{gs}. We have resistive network. One resistance is small r small d other resistance is capital R capital D. We need to find out the voltage at this end with respect to ground. This is ground. What is this voltage v_o? With this polarity we are expressing; v_o with top positive, bottom negative or ground. That is polarity wise it is in this way we are expressing v_o positive polarity here and negative here.

As far as this circuit is concerned this is the current source. One part of the current is through this resistance and the other part is through this resistance. Let us now name this current as i_{rd} and this current is i capital $_{RD}$. In order to know the voltage v_o, we want to write down. How can we write down this voltage v_o? v_o equal to current multiplied by resistance. But one thing to notice here is that the current is flowing from bottom to top. But we are denoting our voltage as the upper end is positive with respect to the lower end, we must write v_o is equal to minus i_{RD} into R_D. What is i_{RD}? That component of the current which flows through R_D can be found out because we are having the current source g_m v_{gs}. One part of this current goes through R_D and that we need to find out. That is nothing but $g_m v_{gs}$ into small r_d by small r_d plus capital R_D. This is the current component and this is already there capital R capital D, so we have expressed the output voltage in this manner.

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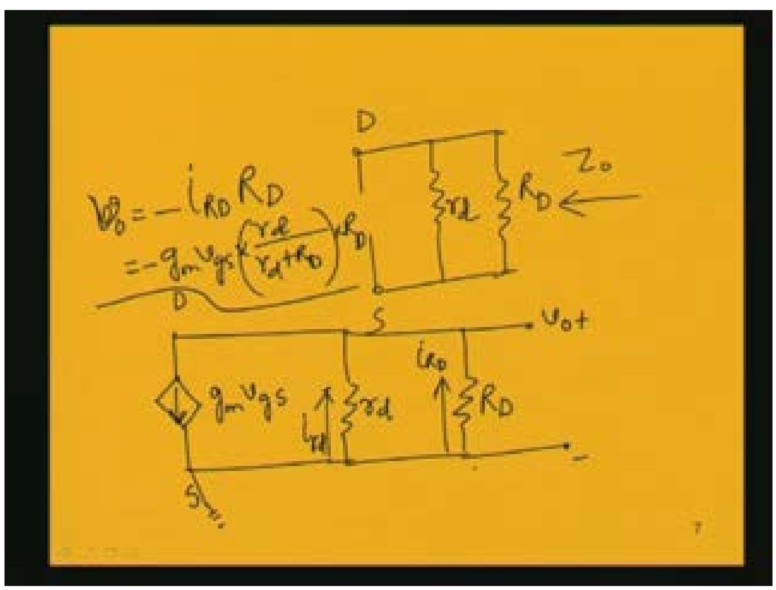

Replace it here in the numerator. Instead of v_o we are writing minus g_m into v_{gs} into small r_d by small r_d plus capital R_D into R_D. The numerator v_{gs} and denominator v_{gs} will cancel out.

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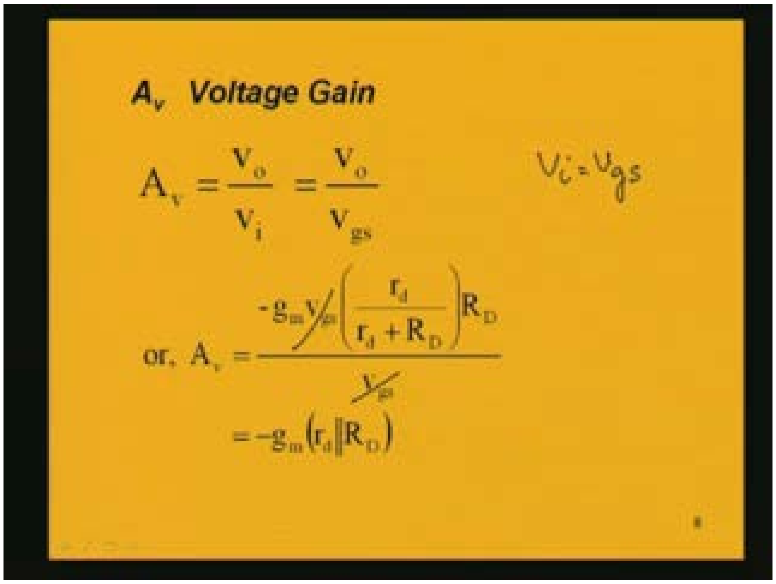

We are now getting rid of all the voltages. What we have with us is the transconductance and the resistance. These are the parameters for the circuit which will define the voltage gain. It is equal to minus g_m into small r_d into capital R_D by small r_d plus capital R_D is nothing but the parallel equivalent of the two resistances say small r_d, capital R_D and that is the voltage gain. Now we can further approximate and simplify the expression because the thumb rule says that if we have the small r_d greater than or equal to 10 times of capital R_D then we can approximate it as capital R_D. Since this is quite high, parallel combination will reach the value which is the lower one so the lower one is R_D so capital R_D. So we are finally getting the voltage gain equal to minus g_m into capital R capital D.

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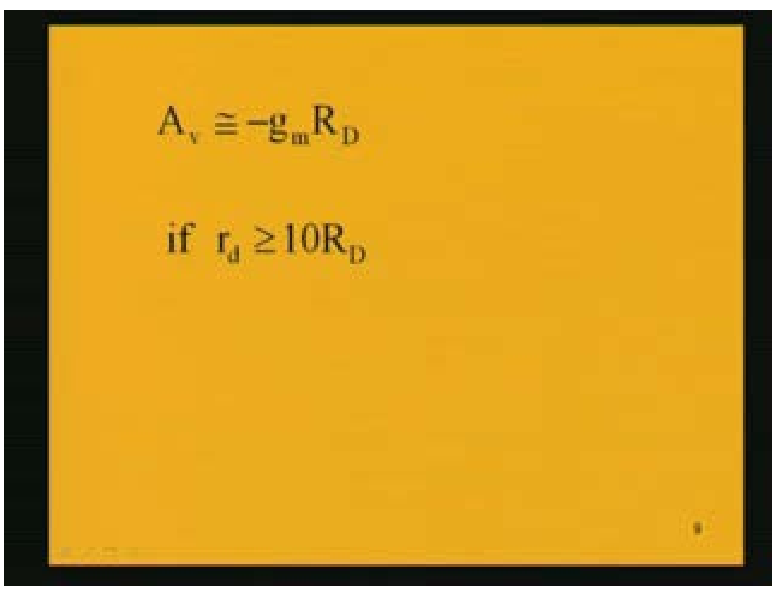

In this voltage divider biasing circuit which was used for the MOSFET amplifier we have seen that the input resistance, output resistance and the voltage gain could be found out from the AC equivalent model using the small signal model for the device by following the electrical laws like KCL, KVL, etc. The circuit which we are using till now is not having the source and load resistances. But even if we plug in the source and load resistances which are practically the case then also it is not difficult to find out. That you can find out very easily. Only we will have a resistance at the source and the resistances at the load

So far we were discussing about one particular configuration of the MOSFET amplifier and that was common source where the source is grounded in the AC equivalent circuit. The input is between gate and the source and the output is between drain and the source. It is similar to the common emitter amplifier which we got in BJT. The other two configurations of MOSFET amplifier are common drain and common gate. Let us now look into these two configurations also. The common drain MOSFET amplifier configuration using the biasing scheme like the one which we just now discussed is having this configuration as shown in figure.

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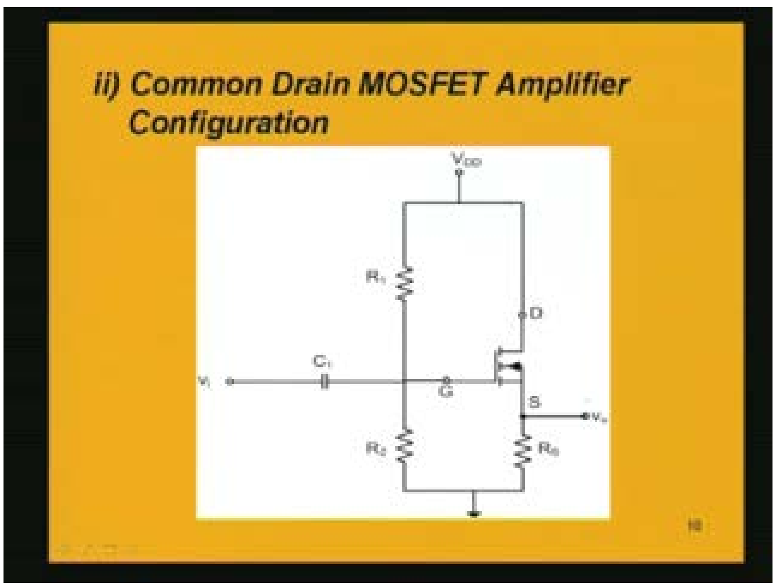

Why do we tell that it is common drain? If we look into the circuit then we see that this drain is directly connected to the biasing voltage V_{DD} and the output voltage v_o is obtained across the source resistance R_S. Input voltage is v_i. In this circuit which is having both DC and AC conditions in it if we analyze separately the AC only then what will happen is if we draw the AC equivalent this V_{DD} will be directly connected to ground. Because in AC equivalent circuit we have this V_{DD} zero, it is it is made zero; it is grounded. So the drain will be connected to the ground. Drain is grounded and the voltage across this resistance R_S is the output voltage. The AC equivalent circuit if we draw for this configuration then what will we get? As usual the input v_i will be there and this capacitance will be simply short circuited.

From the gate terminal if we look into the gate will be connected to v_i and one resistance R_1 will go to ground and the other resistance R_2 will also be going to ground. That is just like your potential divider biasing scheme which we were now using for common source. It is same, it is similar but the other part that means if we look into this drain, drain will be connected to ground.

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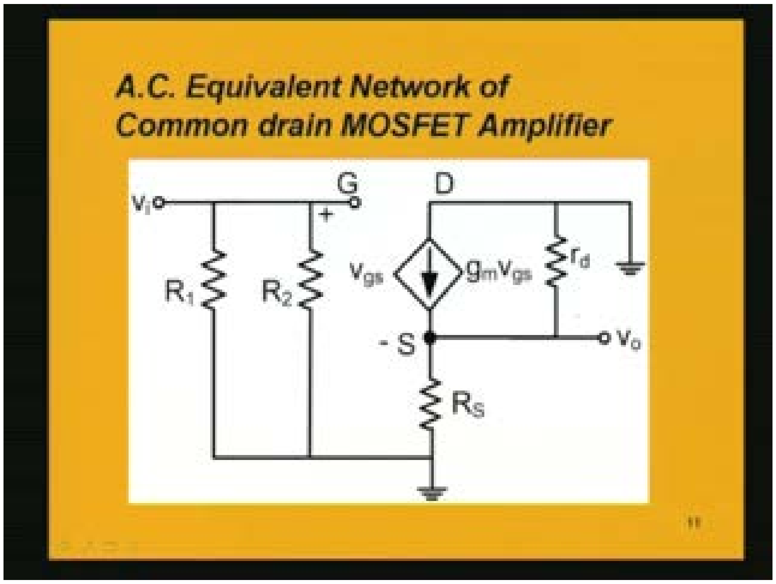

The resistance r_d as usual is between the drain and the source but the voltage v_o which is obtained will be across the resistance R_S. That is this voltage because in the figure you see that this is the voltage across R_S which is the output voltage. This is the peculiarity of this configuration which is different from the common source and if we recall this is similar to the common collector configuration of BJT amplifier. In common collector also, the collector was grounded in the AC equivalent and the output voltage was obtained across the emitter. That was in common collector circuit. Here we get the AC equivalent circuit as shown in this figure. So we can proceed and find out the corresponding parameters like input impedance, output impedance, voltage gain etc., for this circuit because once we draw the AC equivalent circuit and proceed in the similar manner we can find out those parameters. You can try this but let me also introduce another configuration which is the common gate configuration.

In common gate configuration, the gate terminal is grounded in the AC equivalent circuit. Here the gate terminal will be grounded. This is the amplifier circuit. If we want to draw the AC equivalent for this amplifier circuit following the usual steps what we will do is we will make the DC voltages zero and we will make the capacitors having short circuit part and we will bypass those resistances which are bypassed by the short circuited capacitors. If we look this into the circuit carefully here what is done is that the source is biased with a current source I_Q, a constant current source I_Q and there is another voltage V+ for the drain through this resistance.

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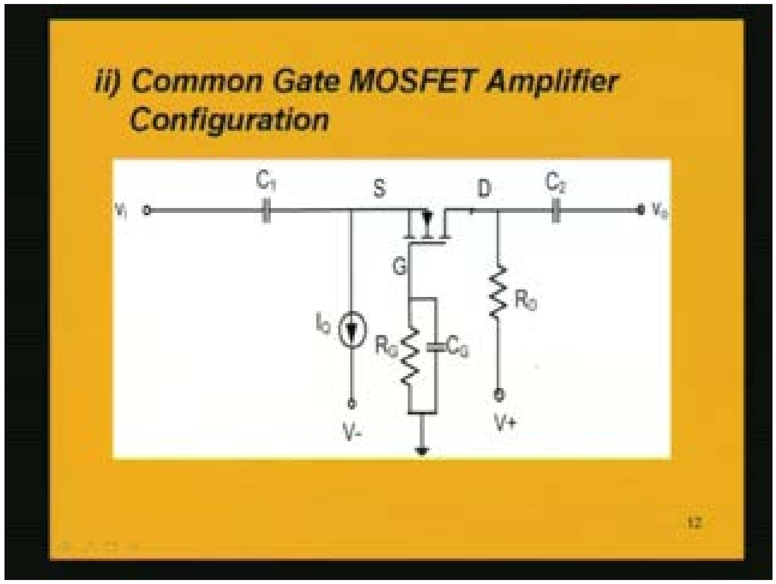

Biasing is a bit different and we now want to draw the AC equivalent circuit for this. To draw the AC equivalent circuit we will make the usual assumptions and what we will do is first and foremost we will make this DC voltages zero.

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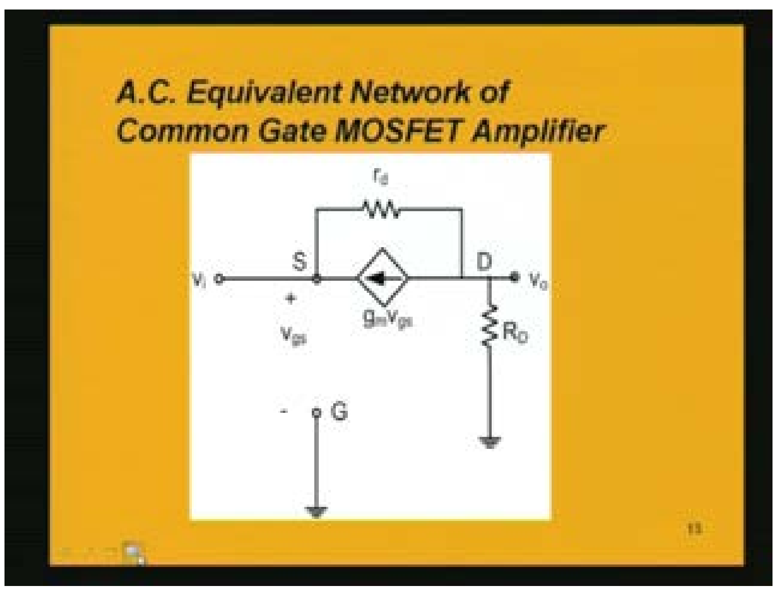

Basically we have the voltage V+ V- zero and the biasing current source also zero. In the equivalent circuit the gate terminal will have a part through this short circuited capacitance C_G. So gate will be grounded. Gate will be grounded and source will have this v_i connected to it. This is open circuit because this DC biasing is zero. As this is open circuited current source there will be no part available in this and the drain will have only resistance R_G connected to it because this voltage also will be zero. Now the whole circuit will look like this. We have a resistance between drain and source, the output resistance. That output resistance practically is almost like infinite because it is having a high value. But exact circuit is having this value R_D but you can approximately make it as open circuit because it is having an infinite value because otherwise that circuit may be a little complex.

In this network the gate terminal is grounded. This is the reason for calling this circuit as common gate. The common gate configuration of the MOSFET amplifier is having the gate grounded so the signal ground which is seen in the equivalent circuit tells you what configuration it is. In order to detect whether it is a common source or a common drain or a common gate configuration we need to look into the AC equivalent circuit. From the AC equivalent circuit we can very easily find out which terminal is grounded and that is the common ground for both input and output or the common terminal. That means input circuit is between say source and ground and the output circuit is between the drain and ground. Input circuit is having the two nodes as source and gate and the output is between drain and gate. We have seen that depending upon which terminal out of the three, source or gate or drain the terminal which is grounded that will be in the AC equivalent circuit and that will lead to the particular configuration in which it is used.

This common gate MOSFET amplifier is similar to the common base BJT amplifier. We discussed earlier about the common base amplifier in BJT. In BJT, the common base amplifier was having the base terminal grounded and common between the input and output circuits. The input circuit was between emitter and base and the output circuit was between collector and base. Similarly here in the corresponding MOSFET amplifier the common base is the common gate. So common gate and common base are equivalent in the two different types of devices and this circuit can be used for finding out all the parameters; that you can try. Here we will have to make this r_d almost like infinite. If we want to simplify it further then very easily you can find out the parameters. We have discussed about the three different configurations and let us do one example for finding out these parameters with respect to the common source amplifier which is having a feedback biasing scheme.

For example we have an n-channel enhancement type MOSFET and we have the values as given in this circuit. This is the gate, this is the drain and this is the source. It is a common source. We have a simple biasing scheme which is the drain feedback biasing scheme. The drain is having the feedback resistance to gate and other components like the coupling capacitors will be there. This is the biasing called as V_{DD} which has a value of 12 volt. Given that the resistance R_D is 2 kilo ohm and this resistance R_F is 10 mega ohm. The coupling capacitance, this is 1 micro farad this is also 1 micro farad. Output voltage is here at the drain terminal and this is the input voltage being applied here. In this circuit from the specification sheet or data sheet some of the data are known. K, the fabrication constant is 0.24 into 10 to the power -3 ampere per volt square. This is given to you. If it is not given to you then we can find out from the transfer characteristic if we know the values of $I_{d(on)}$ and $v_{gs(on)}$. The threshold voltage also has to be known and in this particular example threshold voltage is given as 3 volt. V_T is the threshold voltage and y_d that is the admittance between the drain and the source that is a given as 20 micro Siemens; S means Siemens. That is basically an unit to denote admittance.

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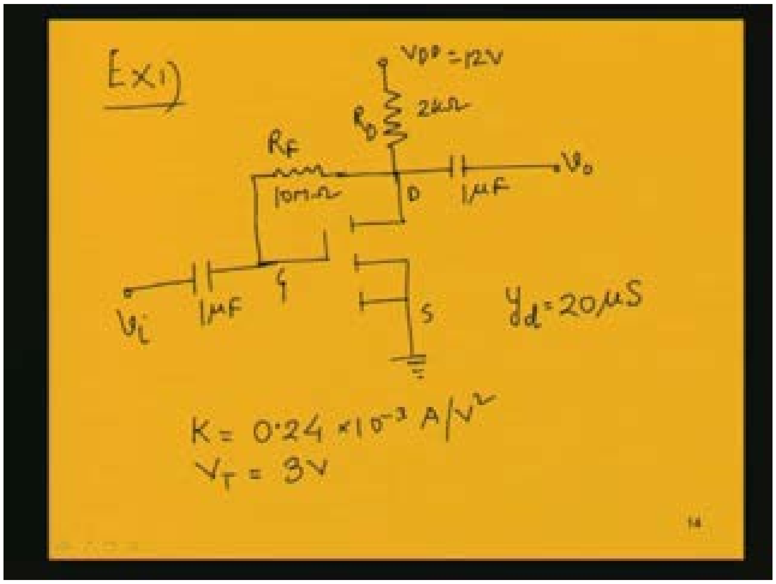

The data given should be enough to find out. We know the K. We need not know the $I_{d(on)}$ and $v_{gs(on)}$ from the data sheet because directly we are given the value of K. Earlier also we tried one example where we were given the values of $I_{d(on)}$ and $v_{gs(on)}$ and from that we could find the value of K provided V_T is known and we could draw the transfer characteristic by finding out the relevant points. If we are not given K we must know what is V_d, $v_{gs(on)}$, $I_{d(on)}$ and V_T. That information is required, but here we are given. In this example we have to find g_m transconductance, resistance between drain and source, the input impedance, output impedance and the voltage gain. You are told that you consider r_d. That means r_d has to be used.

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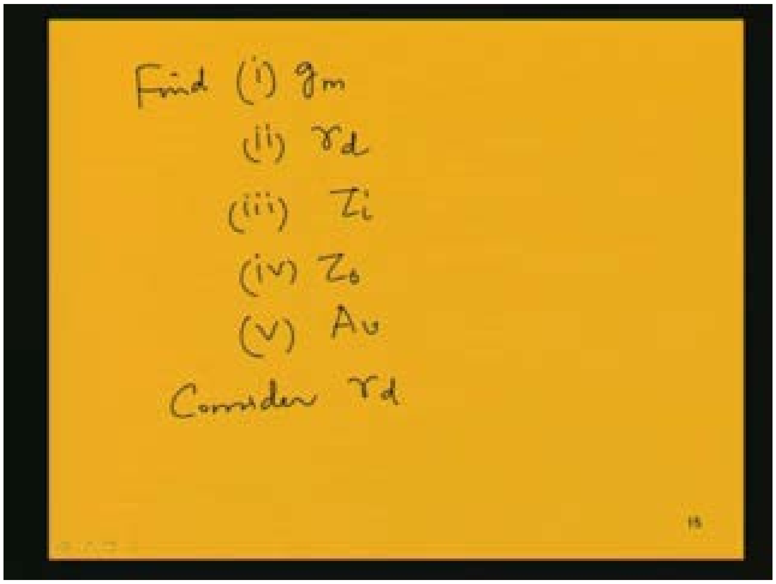

For the common source configuration we have so far found out all these expressions. g_m, the trans conductance can be found out from the relation g_m equal to twice k into V_{GSQ} minus V_T. Q means at the operating point, so the operating point voltage has to be known. In this problem V_{GSQ} is given as 6.4 volt and I_{DQ} the corresponding drain current for the operating point is 2.75 milliampere. That data has to be known. You now put these values 2 into 0.24 into the operating point voltage that means the voltage between gate and source at the operating point or the Q point is 6.4 volt; here 10 to the power -3 6.4 minus 3. You look into the units; this 0.24 into 10 to the power -3 that has a unit of ampere per volt square. That means we have ampere per volt square and here this is volt. This volt and this volt cancel. So what we are left with is ampere per volt. That will be the unit of this transconductance. You have to be careful about the unit. If we calculate this out, it will give you the value of 1.632 into 10 to the power of -3 ampere per volt. We can write in another way. That is 1.632 milliampere per volt or that is also written as 1.632 milli Siemens. This is g_m, transconductance we have found out.

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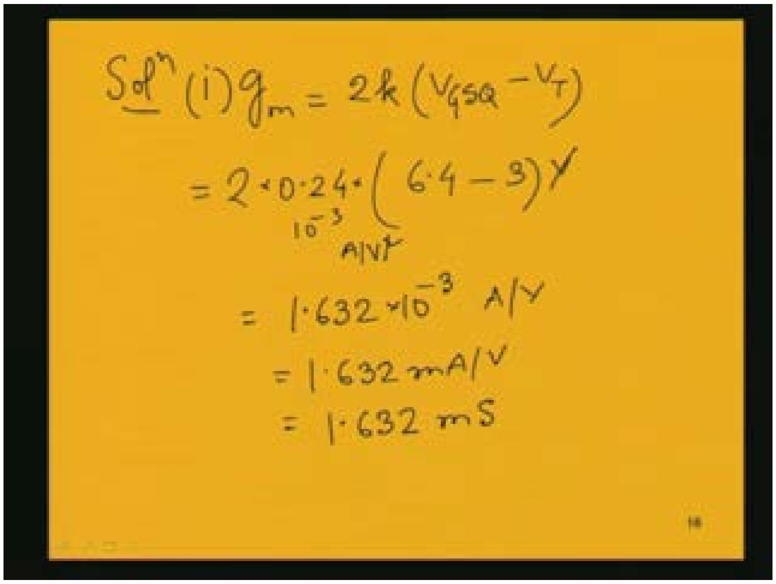

Let us now find out r_d. Next is small r_d. In the data we are given the value of y_d that is the admittance. 1 by admittance y_d equal to the r_d. r_d equal to 1 by y_d; so 1 by value of y_d is 20 micro Siemens, 10 to the power -6. The unit will be ohm because here ampere per volt if we use, the reciprocal will be volt per ampere, in ohm. Finally we will get a value of 50 kilo ohm. This is the value of r_d. It is quite a large value you can see and the feedback resistance R_F is also quite high. It is 10 mega ohm which is used here. So our usual assumptions will be true. But now let us find out exact value without assumptions. What is the input impedance?

Input impedance we can immediately plug in the values of the relevant parameters into the expression or if we want to proceed from the small signal AC equivalent circuit we can proceed in a systematic manner and from first principle can find out so that even if we do not remember the expression we can always find that out from the AC equivalent circuit. That you can try; but now for the sake of completion of this problem let us immediately put the values. We know that Z_i is equal to R_F plus small r_d parallel capital R_D by 1 plus g_m small r_d parallel capital R_D. We are using small r_d. We are not ignoring small r_d, we are using it. Using this by putting the values R_F equal to 10 mega ohm as given in the circuit so let us keep the unit in the order of kilo ohm so 10 mega ohms means 10 into 10 to the power 3 kilo ohms. All the resistances we will keep in kilo ohm order, then it will have conformity. Small r_d we have found to be 50 kilo ohm; so parallel with capital R_D for this circuit is 2 kilo ohm. 50 parallel 2 divided by 1 plus g_m, transconductance we have found out to be 1.632 into 10 to the power -3 ampere per volt. That is nothing but 1.632 milliampere per volt. Since we are using kilo ohm order let us use milli unit because then milli and kilo will cancel or it will make unit one. So 1.632 into 50 parallel 2; so the final unit what will it be? It will be in kilo ohm because in this denominator if you see we have here kilo ohm and here it is milliampere per volt means milli and kilo will have unit one and the other will be ohm.

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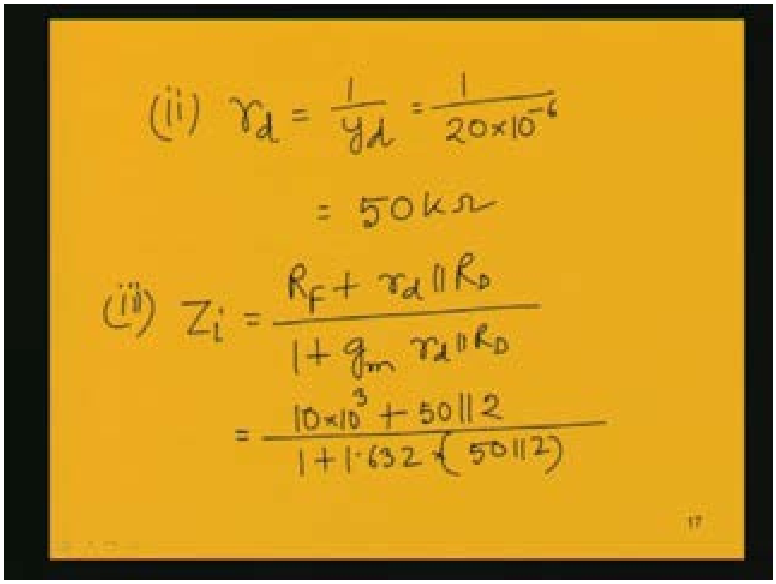

It will be same. Otherwise everything if we want to take it into ohm then that has to be multiplied by 10 to the power -3. This has to be again multiplied by 10 to the power 3 in this way. 50 parallel 2 if we calculate that is 50 into 2 by 50 plus 2, this value comes to 1.923 kilo ohm. What will be Z_i? so Zi equal to 10 into 10 to the power 3, plus 50 parallel 2 which is 1.923; in the denominator we have 1 plus g_m r_d parallel capital R_D that is 1.632 into 1.923. This calculation if we do, we will get a value of 2416.89 kilo ohm because the unit is in kilo ohm both in the numerator and denominator. We get it in kilo ohm but we can write it in mega ohm. It is a high value. If we multiply with 10 to the power -3, it will be in mega ohm; 2.42 mega ohm.

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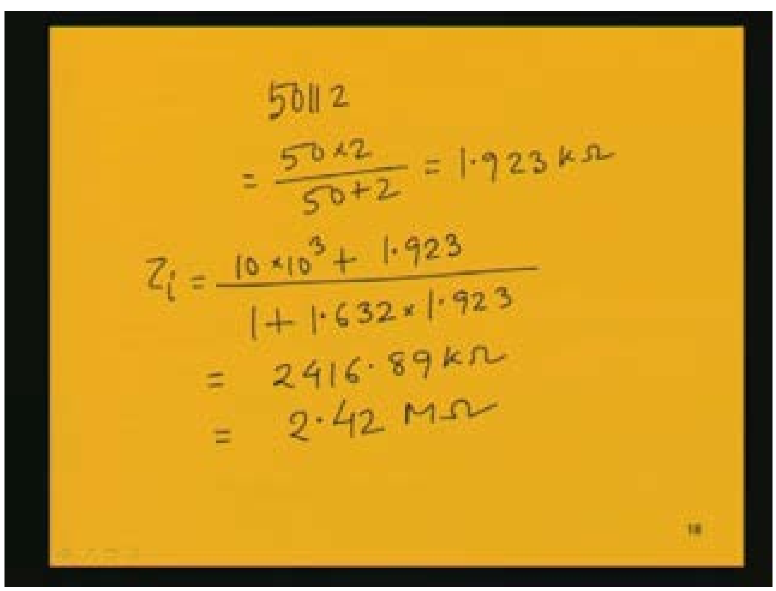

The input resistances as you can see it is quite high for this amplifier. What about the output impedance? Output impedance, we know that, it is a parallel combination of the three resistances R_F small r_d and capital R_D. Capital R capital F is 10 mega ohm, 10 into 10 to the power 3. We are writing all in kilo ohm order. So this is 50 kilo ohm parallel 2 kilo ohm. This part we have already done. 50 parallel 2, we have found out. This is the value 1.923 kilo ohm. Finding the parallel combination again it is 10 to the power 4 into 1.923 by 10 to the power 4 plus 1.923. If you do this calculation you should get a value of 1.923 kilo ohm.

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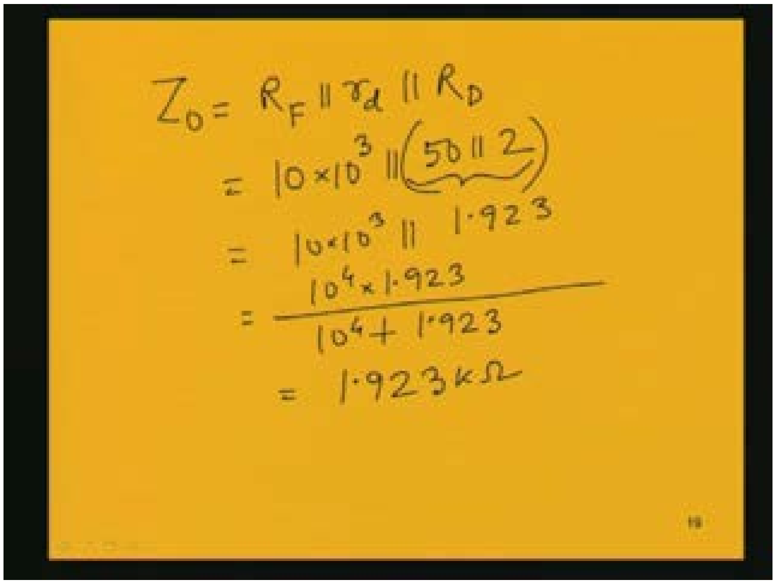

Check this value. Because this is a very high value 10 to the power 4 kilo ohm and this is a small value approximately the parallel combination ultimately will give this value and what will be the value of the voltage gain? Voltage gain; we know the expression for voltage gain is minus g_m into r_d parallel capital R_D parallel capital R_F. This part small r_d parallel capital R_D parallel capital R_F we have already found out to be 1.923. Basically voltage gain is nothing but minus gm into Z_O. $-g_m$ we have found out to be equal to 1.632 milli Siemens. Let it be 1.632; because it is milli it will be in confirmative with the kilo. Here we are writing 50 parallel 2 parallel 10 to the power 4; 1.632 into this part we have already calculated. That value is 1.923 and finally we get a value of -3.14 volt.

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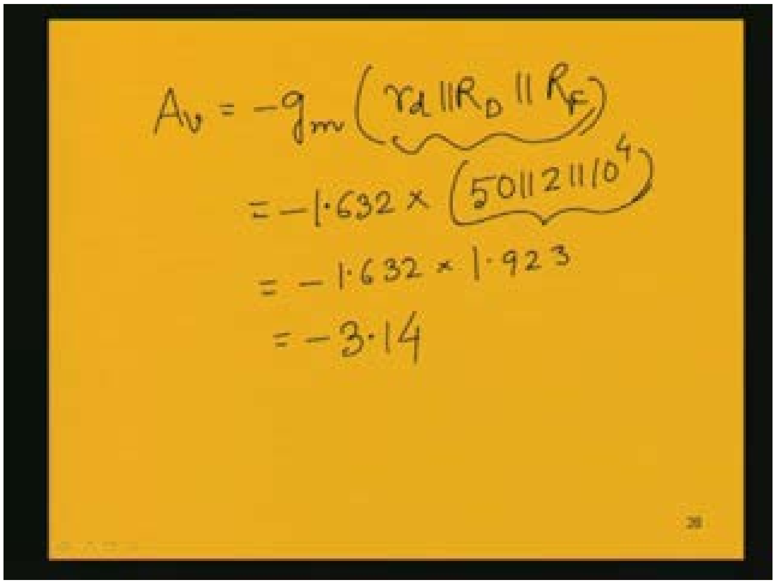

This is the voltage gain if we consider the small r_d which is the resistance between the drain and the source.

One thing you can check. In all these calculations if we now do not consider the small r_d which is a very high value or assume to be infinitely high then there will be a difference between the values what we have obtained and what we will get without considering or considering r_d to be infinite. For example in this voltage gain if we have an infinite resistance r_d say for example exactly horizontal I_d characteristic verses V_{DS} then what will be the voltage gain? That can be checked actually by just calculating without r_d what will be the value of A_v? If we do not consider small r_d or if small r_d is very high also as R_F is very high, R_F is 10 mega ohm and small r_d value is equal to 50 kilo ohm and capital R_D equal to 2 kilo ohm.

You think about these three resistance values. Out of these three resistances R_F is quite high as compared to the other two. It is 10 mega ohm. This resistance R_F is far greater than the parallel combination of r_d and capital R_D because in our earlier assumptions we have seen that if R_F is very, very high than this whole parallel combination the voltage gain can be simply written as $-g_m$ into the parallel combination will be finally boiling down to small rd parallel capital R_D. That can be verified actually. What is the parallel combination of small r_d and capital R_D? We have seen that value is equal to small r_d parallel capital R_D; 50 parallel 2 gives 1.923 kilo ohm. 1.923 kilo ohm is the value of small r_d parallel capital R_D, 1.923 kilo ohm. Here we have 10 mega ohm, so in comparison with 1.923 kilo ohm 10 mega ohm is quite a high value. So very conveniently or without any violation we can simply replace the whole expression of this voltage gain by simply minus g_m into r_d parallel capital R_D. Further simplification can be done again because we see that here small r_d is greater than equal to 10 times R_D. That has to be satisfied if we want to further make an assumption.

What is 10 times r_d? 20 kilo ohm. We have 50 kilo ohm and here it is 20 kilo ohm. It has to be greater than or equal to; it is greater than 20 kilo ohm. So ultimately we get minus g_m into capital R_D. If you put these values it will be minus 1.632 into r_d is 2. So we will get a value of -3.264.

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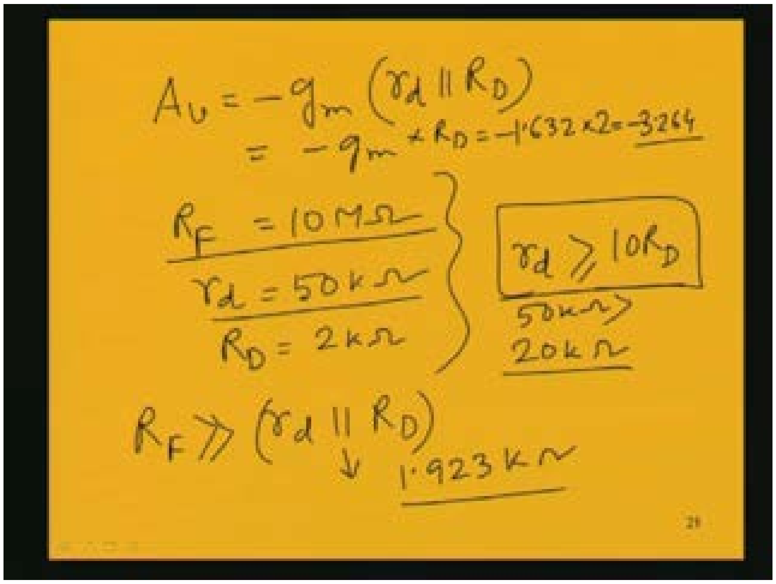

Compare this value -3.264 A_V, with this. This is almost very close to whatever we have got with the exact calculation. It is basically around -3 voltage gain what we get.

Today we have discussed about the potential divider biasing scheme applied to the common source MOSFET amplifier using e-type or enhancement type MOSFET and we have found out all those required parameters like input impedance, output impedance and voltage gain. Also we have seen the other two configurations of common drain and common gate amplifiers and we have seen their small signal models also. From the discussion we could finally find that the resistances if we properly choose and design then the final gain or the impedances which actually is involving all the resistances in the network can be further simplified and we get an expression for the gains or the resistances quite simple if certain conditions are met which are the thumb rules generally used for design. In the example also we have seen that using this approximation finally whatever we have got as the voltage gain it is a very close expression that was obtained using the exact expression. In this way we can proceed to find out the AC equivalent model and go on to design an amplifier required for our purpose. While designing we will have to choose the components in the amplifier circuit very carefully.