Analog Electronic Circuits.
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Lecture-50.
Op-Amp Offsets, Compensation and Slew Rate.

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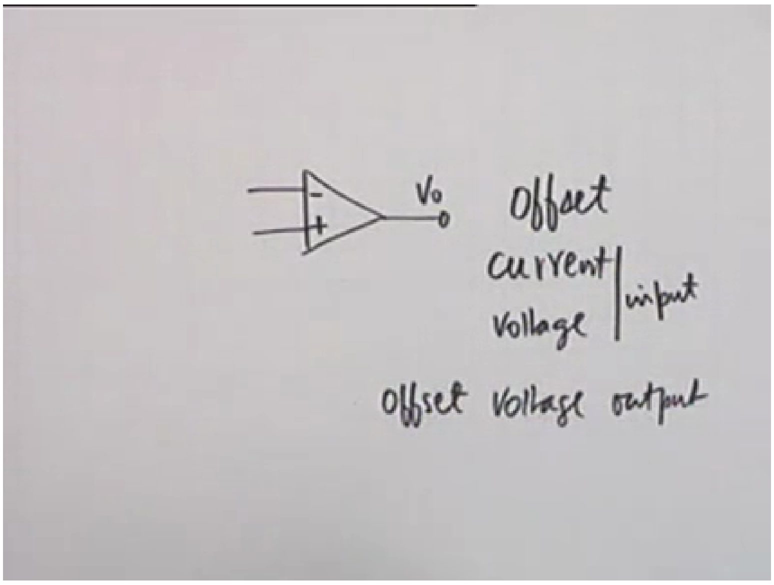

To the lecture now, 50th lecture, last but one, tomorrow will be last lecture. And we will discuss, we started discussing Op-Amp offsets, then Compensation and slew rate, these are the imperfections of an Op-Amp which would like to understand and discuss. Offset by definition is any phenomenon which makes the Op-Amp output nonzero if the signal applied is 0. Without any signal, without any signal if the Op-Amp output is nonzero, we say the Op-Amp shows offset. An offset can be either current or voltage and this can be either at input or at output.

At input we talk of offset input current and offset input voltage, at the output, since we do not measure the current, we only say voltage offset at the output. Offset voltage output and the offset voltage output arises because there are offsets at the input. At the input offset can be due to 2 reasons, one is current offset and the other is voltage offset. Now as I said the offset voltage output could arise due to, any offset arises due to mismatch of the 2 transistors at the input stage. Offset can also occur at succeeding stages but it is the input stage offset which is the most important.

And the reason is obvious because the input offset voltage or current undergoes much larger amplification than any offset arising at any intermediate stage, all right. Most of the gain occurs in the 1st stage, the new make up for the dynamic range, keeping the dynamic range, we did not control, you make up for the rest of the things. And therefore the input offset is the most important and that is, that occurs at the 1st stage which is a differential amplifier basically acting as a transconductance amplifier. That is the output impedance of the 1st stage, differential stage is high, so basically it supplies current to the next stage, the input as usual is a voltage.

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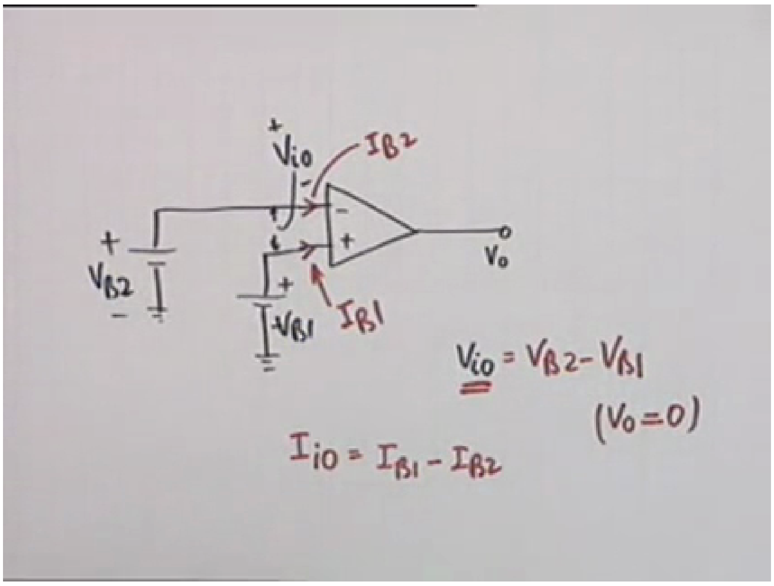

Now we had drawn a simple model of the Op-Amp taking account of the offsets and we are considering DC offset, offset arises basically because of mismatching of the 2 bias currents and the 2 VBEs, okay, the 2 base emitter voltages. And the simple model that we had shown was that if this voltage is VB 2 and this voltage is VB 1 and there is a difference between the 2, VB 2 minus V B1, if it is not equal to 0, then this appears as a signal between the 2 input terminals and therefore it produces an output. And this voltage is called VI0, VI0 can be either positive or negative.

There is no guarantee which terminal which have a higher voltage, therefore it could be positive or negative. But for uniformity sake let us say this voltage is VI0 with this polarity, plus and minus. I am intentionally confusing the terminal so that you can keep track of the sign of the offset voltage. Offset voltage VI0 can be either positive or negative. In addition there are 2 bias currents, let us note, let us call the bias currents as IB2 and I B1. VI0 is let say

VB 2 minus VB 1 and this is defined, the input offset voltage is defined as the voltage appearing between the 2 input terminals when the output is 0, this is the definition.

Input offset voltage VI0 is the difference between the 2 input terminals under the condition that V 0 equal to 0. You understand what I mean? This is the general nomenclature that has been accepted by all manufacturers. They specify VI0, and obviously if there is a VI0, there would be a V0 and to annul the offset voltage you shall have to apply a voltage in the opposite direction, agreed. So what they do is, since the office, they have to, they specify this by actual measurement, they do not make all these calculations and all that, actual measurement.

Actual measurement they can make, a voltage appears at the output, it is very difficult to measure the input voltage because the input voltage will be very small quantity of the order of microvolts for example. And therefore what they do is, they apply a potential at the input such that the output is 0 and this potential is measured by indirect means. Since it is a very small voltage, it is measured by indirect means, okay. So the input offset voltage is defined like this. Similarly the offset current I I 0 is the difference between these 2 base, these 2 base currents.

That is and it is defined, it can also be positive or negative, now let us define as I B1 minus IB2, okay. It can be positive or negative, IB2 may be greater, then this is negative, if I B1 is greater, then this is positive, I 0. And this is also measured under the condition of V0 equal to 0. The definitions, the manufacturers specify the input offset voltage, the input offset current under that condition of 0 output voltage. In other words there is an offset, there shall appear in output voltage, you annul that output voltage by applying an input current in the opposite direction, okay. This is the general nomenclature, general specifications that are given in the case of an Op-Amp.

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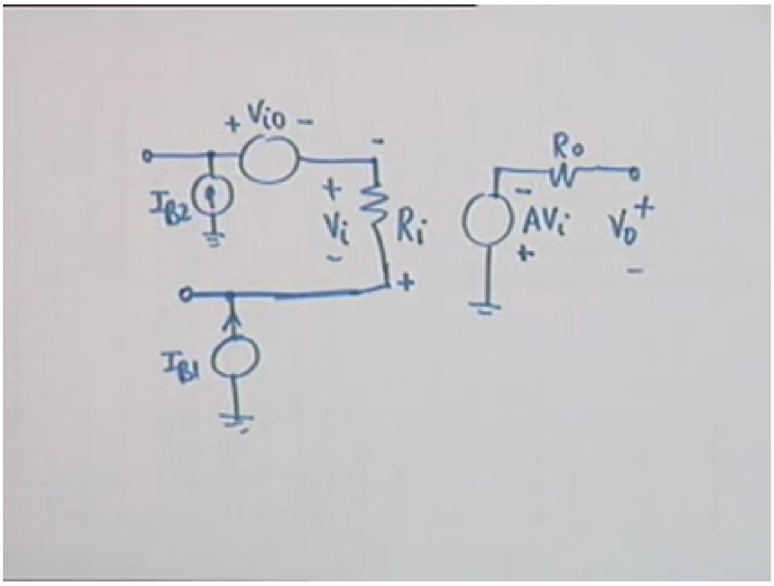

Now obviously then our Op-Amp model, Op-Amp could be modelled in a slightly different manner by taking the difference between the offset voltage as appearing across, appearing at one of the terminals, okay, the difference between the 2 appears at one of the terminals like this. And then the input, that is between the non-, between the inverting and noninverting, if the impedance, if the resistance is RI, then this is the noninverting terminal. And what we do is, we brings out the 2 terminals and apply 2 bias currents as current generators.

This is one of the model that is often used, IB2 and the bias current IB1, the difference between them is high I I 0, input offset voltage. If this is considered as VI across the 2 terminals, due to the combined effect of IB2, I B1 and VI0, we are not showing VI0, VB1 and VB2 separately, we have combine them into one. And the model of the Op-Amp would be AVI, is A is considered positive, then the polarity would be minus and plus because VI has been considered plus at the inverting terminal, you must keep track of this. The gain usually is specified as a positive quantity.

If the voltage is of this polarity, obviously the output voltage will be of the other polarity, this and you have an output resistance are 0 and this is V0, this is a model of the Op-Amp taking input offsets into account. There are several definitions that are used in characterising or specifying an Op-Amp and I will go through this, these terms which you must be able to read and judge how good the Op-Amp is, okay.

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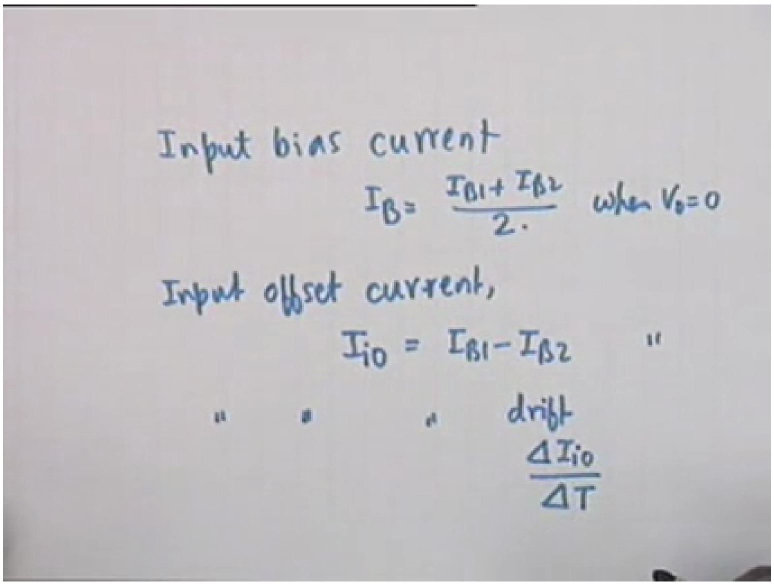

One of the specifications is the input bias currents. Obviously this does not mean anything because there are 2 inputs and the bias currents I B1 and IB2, you have to specify 2, but what the manufacturers usually specify the average of the 2, I B1 plus IB2 divided by 2, okay. When again under the conditions when V 0 is equal to 0, all right. Input offset current, as I said, this is I I O, input offset and it is defined as I B1 minus IB2, again when V0 is equal to 0. There is also defined input offset current drift, this is also specified. This drift is the trigger to temperature, that is this is defined as Delta I I O by Delta T, if temperature changes, how does the input offset current change, okay. This changes because beta changes, VBE changes and therefore the offset will also change.

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We do not have a specific, it simply says Delta I I 0 by Delta T.

(())(12:16) under particular condition?

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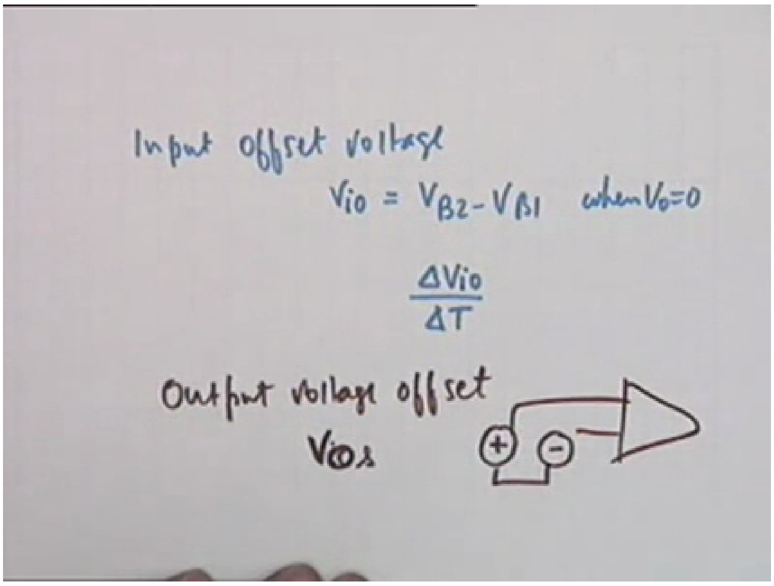

It is under no particular condition, I does not depend on the load, load is far away from the, it is the absolute value. Delta, see I I 0 is defined as V0 equal to 0, so Delta I I 0 Delta T is obviously with respect to the same condition. And then input offset voltage, as I said this is denoted by VI0 and this is VB 2 minus VB 1, for unknown reasons we take V2 minus V1 when V 0 equal to 0. And once again you can also define an input offset voltage drift as Delta VI0 by Delta T, this is also specified by the manufacturer. Normally, naturally, the smaller the value the better is the Op-Amp, okay.

(())(13:24) some particular temperature?

Room temperature, room temperature is taken as 25 degree centigrade? No, it is taken as 300 degree K, which means 23 degree centigrade.

27.

27, I beg your pardon, 27 instead of 25. Room temperature is taken as 27, that is the reference with respect to all other temperatures are specified. Okay, now next is output voltage offset, this is VI, now this is V0 instead, I mean if you want to specify offset, then you call its V0S, V0S, that is the output offset, I cannot use V0, we can even say V00 if you so desire, that is also come all right. But this is defined under the condition that the plus terminal, the inverting, noninverting terminal and the inverting terminal of the Op-Amp are connected together, okay.

That is a common mode voltage is applied, no, no common mode voltage is applied, they are simply connected together. So whatever voltage appears at the input shall be a common mode voltage, then you measure the output, this is called, this is the definition of the voltage offset at the output. There are few other terms which we shall, it is good to know at this stage because that will complete the characterisation or specifications of an Op-Amp.

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The 1st is input common mode range.

Why does the output voltage offset we do (())(15:12).

You see even if there is no signal and the 2 inputs are connected together, if there appears in output, obviously that is an output voltage offset. But this offset arises because of what? Not input offset voltage, because the 2 inputs are connected together, it is due to the difference in the bias currents or current offsets, okay, that is the benchmark. Input common mode range is the common mode input signal range which can be applied without the differential amplifier becoming non-linear. That is the differential amplifier, the Op-Amp characteristic, I should not say differential amplifier, the Op-Amp characteristics, this is input, this is a common mode signal range which can be applied to the Op-Amp without the output going into the non-linear region.

It is a very qualitative things but it gives an idea as to what common mode signal you can apply, all right. Then similarly input differential range, differential range is the maximum differential signal, differential signal that can be applied to the OA, operational amplifier input terminals, again without the output going into the non-linear region. And you know that for differential amplifier it is approximately, what is the range? For VT, 100 millivolts, approximately 100 millivolts. So this is defined for the total Op-Amp, input differential range.

Then a quantity which is also somewhat non-analytical, a qualitative, output voltage range, you know that the output voltage, what is the maximum output voltage that you can get out of it differential amplifier? If VCC and V EE are equal, then the maximum is 2 VCC, plus VCC and minus VCC, maximum range, okay, 2 VCC. Often you cannot go up to VCC, you must stop at a few volts before VCC this is because either the voltage goes into saturation, from both sides it goes into saturation, you must avoid that non-linear region.

So a few volts, maybe if the supply is plus -15, plus minus12 is usually specified by the manufacturers, this is the output voltage range, your output voltage must not exceed plus minus12, then you will get into the non-linear region. Then a quantity which you have not come across so far is full power bandwidth, full power bandwidth. This is very much, very much related to output voltage range. Full power bandwidth is the maximum frequency of a sinusoid, maximum frequency of a sinusoid for which the output can reach the limit of output voltage range. You understand this?

It is the maximum frequency of a sinusoid for which the output can reach its limiting values. Now why is that a maximum frequency? Every Op-Amp has a bandwidth, whatever connection it is, there is a bandwidth, okay, it cannot go beyond that, if it goes beyond that obviously the output shall decrease. If the frequency increases beyond the full power bandwidth, then you cannot reach plus minus12, that is what it says, okay. So these frequencies shall be specified, it is a bandwidth specified in hertz, so many hertz.

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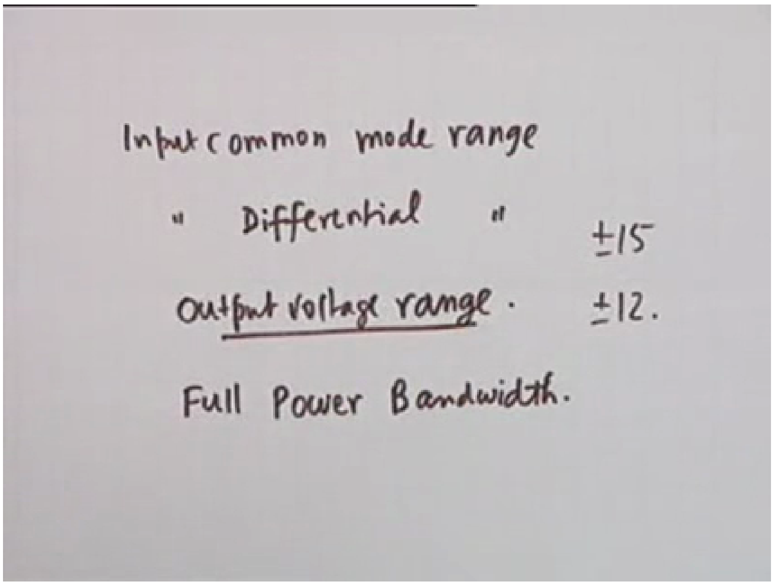

Then there is a quantity called PSRR, that is the power supply rejection ratio and it is defined as, there are 2 power supplies basically in Op-Amp, plus and minus. Is one of them changes by small m, let say from 15 to 15.001, it is all stabilised with Zeners and voltage regulators but even then suppose it changes, due to the temperature change or some other change, how much does the input offset voltage changes? So it is a ratio of change in VI0 divided by change in one of the supplies, one supply keeping the other fixed, okay. Is this point clear?

One at a time, one supply changes, how much is the input offset, okay. And this ratio is PSRR, PSRR normally used to be very very high, very very high and this is why the voltage regulator chips are so important. No Op-Amp can be driven without a stabilised power supply. Finally the quantity that is slightly mysterious but we shall, we shall require this, it is called the slew rate. It turns out, one of the manifestations of slew rate, we will approach it from different angles but flow rate, all rights, 1st definition, it is the range of change of the output voltage dv0 by dt Max, maximum rate of change of the output voltage at large voltage inputs, okay, under large conditions, under large signal condition.

We shall see why this arises but the external manifestation is that if you apply a step, if you apply a unit step, okay, what do you expect? After all the Op-Amp can be modelled by a single pole we shall see, it has to be a single pole, dominant pole model. If it is a single pole, then it behaves as a lowpass circuit, in a lowpass circuit if you apply a unit step, lowpass circuit simplest example is series R, shunt C. If you apply unit step, the output voltage should rise exponentially, it is a particular phenomenon in an Op-Amp, large gain Op-Amps like this that the rise is linear. I sufficiently large signals, the rise is not exponential, it is linear.

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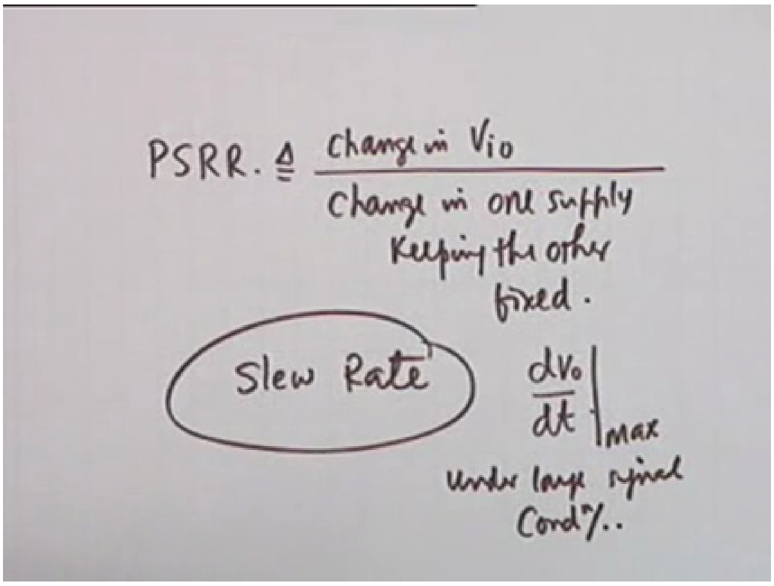

The maximum linear rate of rise that you can achieve is called the slew rate. We shall go into further details of this and see why this arises and what is its value. But 1st let us clarify some of the concepts of offset by taking some simple examples, okay. 1st let say we have an inverting amplifier with 2 resistances R and R prime, R prime is 1 meg and R is 100 K. So the gain would be how much? 10, okay, it is a gain can amplifier and this is grounded, this is usually how usually we draw the Op-Amp, correct. It is given that VI0 is equal to 0, please follow these simple calculations carefully.

There are some simpler find assumption is an very simple calculations are required, then the concept of offset gradually seeps in. VI0 is equal to 0 and the input voltage offset is 0 but the base currents, the 2 input currents are equal. So there is no input offset either, there is no input offset current, I B1 is equal to IB2 equal to IB, the manufacturer definition, the average value of the 2 is 100 nanoamp, okay. Now you are required to find out V0, output voltage, all offsets are measured with the inputs connected to ground, no signal, under no signal condition. No signal condition means that we have to ground this, what is V0?

The question is, it is given it is an inverting amplifier of the gain 10, 10 given that input offset voltage is 0, the 2 bias currents are also equal, there is no input offset current either but this current is 100 nanoamp there into both in the bases, both the bases, will a voltage appear or not and if so what is this voltage? Okay, the solution is extremely simple, you see because of virtual ground, this point is virtually grounded. If this is grounded, if this is grounded…

(())(25:13).

Pardon me?

Why did not you ground the other terminal?

Offset voltages and currents are always measured with no signal. No signal means not open, it must be connected to ground.

How do you measure the inputs offset voltage by grounding the both the terminals, input terminals are grounded.

Now, if I, if I put this to ground, I will measure between these 2 points. You see if both the inputs are grounded then you will have an objection because both inputs are connected together. But if it is connected to the ground through a resistance, the input offset voltage still appears here.

Then the assumption of virtual ground will not be valid here?

Will not be valid but we will assume in calculations that it is valid. All that it requires that the gain should be large, that is all that required. So we assume that the gain is of the order of 10 to the 6, so that the potential is virtually 0. If it is 0, then obviously no current flows through capital R, agreed. If it is 0 and 0 here, no current flows and therefore the bias current which is IB2 must, like this, okay, IB2. And therefore V0 is simply equal to IB2 multiplied by R prime. Is the point clear? If this potential is 0, no current in R and therefore the current must come like this.

And therefore V0 will be simply IB2 multiplied by R prime which is 100 times 10 to the -9 multiplied by 10 to the 6 volts and this is equal to 100 millivolts. Now you see the phenomena, you see the peculiarity that even if there is no input offset voltage, even if my there is no input offset current the base currents are exactly identical, still an output offset voltage appears, that appears, can you guess the reason? The reason is that the 2 inputs are not under identical conditions. One of the inputs is connected to ground through 100 K, this one is connected directly to ground.

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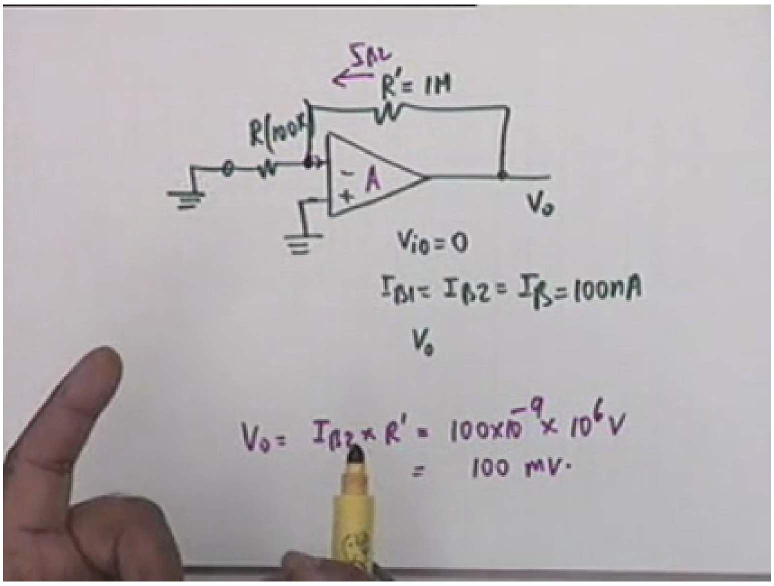

The remedy for this, there is no input offset voltage or current, if you want low output offset voltage, the remedy is that you connect a resistance here. Let us see what happens, this is part B of this exercise. Suppose we connect a resistance, we call this resistance R1, this is R, this is R prime and this is V0, okay. We want to choose R1 such that V0 is 0 when VI0 equal to 0, I B1 equal to IB2. Well it turns out that this resistance can take care of the condition to even if I B1 is not equal to IB2, let us see how. Since V0 is 0, this is our assumption, we want to make V0 equal to 0, therefore R and R prime are virtually in parallel. Is that clear?

Therefore the current I B1, was it IB2 or I B1, IB2, let this current be I B1. Since V 0 is 0, R and R prime are in parallel, therefore V minus, that is the voltage at this point would be equal to minus IB2 multiplied by R parallel R prime, agreed. This is a voltage at the inverting terminal, whereas the voltage at the noninverting terminal is minus I B1 multiplied by R1. And therefore, therefore the condition for V0 equal to 0 should be that no voltage would appear visually 2 points, which means that V0 equal to 0 implies that I B1 R1 equal to IB2 R parallel R prime.

Even if the 2 bias currents are not equal, that is even if there is input offset current, you can compensate for this by using another resistance R1. Normally the voltage here is still 0, okay, if there is no bias current, if the bias current is 0, then it does not matter, it is virtually grounded. But if there is a bias current and there is an offset input current, everything can be taken care by introducing another resistance. And therefore whenever you see in the textbook or an experiment manual or manufacturer specifications that the inverting amplifier is like this, it is implied, you see they cannot show you what resistance it is.

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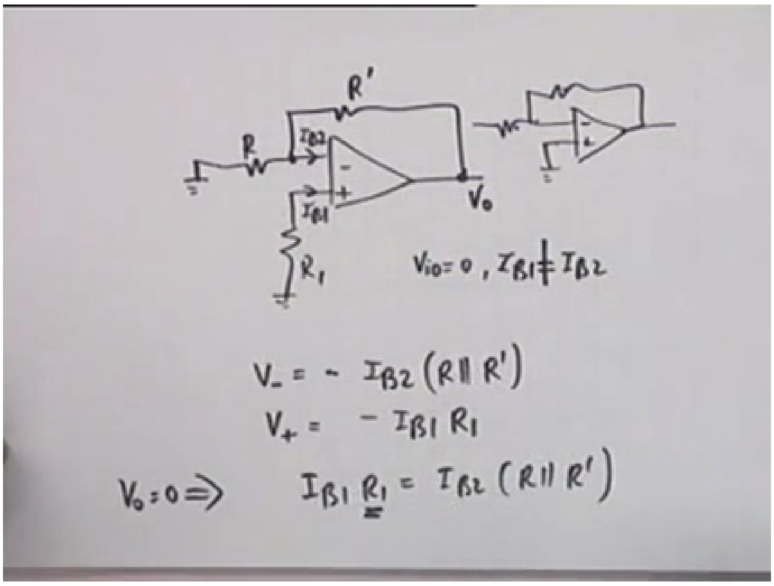

It is implied that this resistance, this is connected to ground through a resistance which is approximately the parallel of these 2. This will drastically reduced the offset voltage and current, okay. In this particular case if I B1 is equal to IB2, then R1 that is required would be 0.1 meg parallel 1 meg, which is equal to 90.9 K, this is required for offset balancing.

(())(31:27).

Pardon me?

Is the gain affected by (())(31:29).

Is the gain affected, no, the gain is not affected. The gain is not affected because as far as easy is concerned, this is 0 potential.

What about the problems in the fabrication of this, such a high resistance value?

It is not fabricated, it is connected from outside. When you use the op amp, you have to connect this from outside because you connect R and R prime also from outside depending on what gain you want. These are not internal to the op amp, these are to be added. Now using the results of the previous part, that is you have, what was this value, 100 K R, R prime was equal to 1 meg, negative, positive, this is 90.9 K. Now suppose in this, in this Op-Amp there is an offset current I B1 minus IB2 is 20 nanoamp. We connected this resistance assuming that I B1 was equal to IB2, okay.

We assume that I B1 is equal to IB2, now if this is not true, if this is not true, then how do we, if this is so, what is the output voltage under this condition, okay? Now see the, how do I calculate this? We argue like this, IB2, look at this argument, IB2 is I B1 -20 nanoamp if, this is I I 0, input offset currents, therefore it is I B1 minus I I 0. If II0 was 0, then there would have been no output voltage, agreed. Because if I B1 is equal to IB2, we have already compensated for this. And therefore the effect of I I 0 can be modelled by assuming I B1 equal to IB2 equal to 0.

But there is a perturbation on IB2 of a current I I 0. Is the point clear? And this of course has to be grounded, the effect of I I 0 can be modelled by 0 current here but a small current I I 0 here. Why in the other direction because it is IB2 minus I I 0, I B1 minus I I 0. All right. Now since there is no current here, this potential is 0, agreed, this potential is 0, so what about this potential? Also 0, so no current flows through R, this, therefore must flow like this. Therefore V0 would be equal to minus I I 0 times R prime which in this case comes out as -20 millivolts, all right.

These are the various things people calculate to make compensation and so on. In the point clear? Let us complicate this matter further. Suppose…

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Which current? Oh, you see if I take IB2 here totally and IB1 here, it is only the differential current that is causing an output voltage. So we could assume, we could as well as that IB2 is equal to I B1, that is the 2 currents are equal, this is the perturbation, we only take care of the perturbation. Because the common current causes V0 equal to 0. The circuit is linear, therefore proposition is applied. Yes…?

When we apply the virtual ground and negative terminal, that will only happen if the positive terminal is grounded.

That is right, but now it is not grounded, it is connected to a 90.9 K but equivalent current through this is 0. And therefore this potential is 0 and therefore this potential is 0, okay. This is simple kind of argument that one uses.

If the current in the 2 terminals, inverting and noninverting terminals is not the same, then in the idea of virtual ground actually valid or not?

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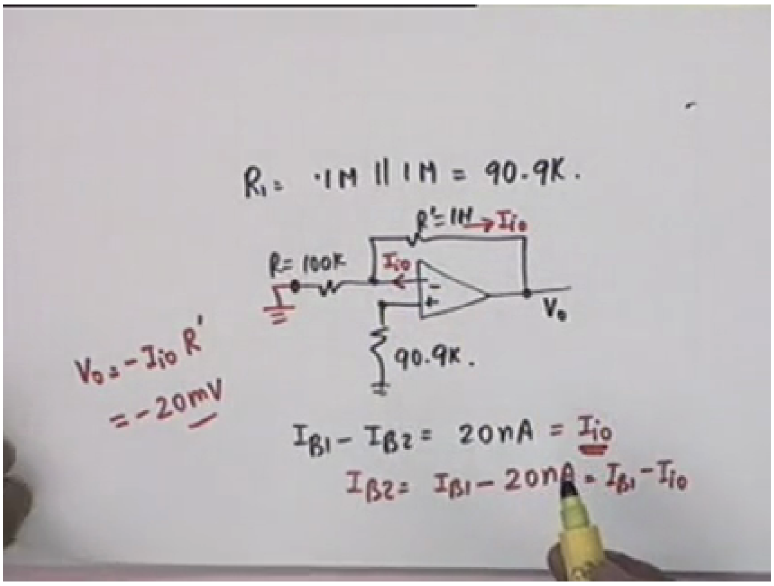

Now that will be no virtual ground, if there are 2 currents here which are not grounded, if there are currents here which are non-equal, unequal, virtual ground can be restored by taking the difference current here. Okay, so that this potential is made 0. Now let us complicate this matter further. Suppose I I 0 equal to 0, no input current offset. But there is a VI0 which is 5 millivolts, okay, so you are required to find out what is V 0 under this condition, for the same, for the same circuit that is we have R, R prime, inverting, noninverting and this is R1. For the same circuit there is no, no input offset current, VI0 is 5 volts, 5 millivolts, okay.

Now if that is so, since there is no input current offset, well this potential is still 0 and this potential is 5 millivolts, therefore the current through R is VI0 divided by R, the current through R is VI0 diverted by R. And where should this current go from? No input offsets, so both the current can be assumed to be 0, so it must come like this, right. And you can easily show that V 0 would be equal to VI0 one plus R1 by R, R prime by R. Very easy to show, V0 is this I into R1 plus R, okay. And VI0 is I into R and therefore this is the ratio, this is the gain 1+ R prime by R.

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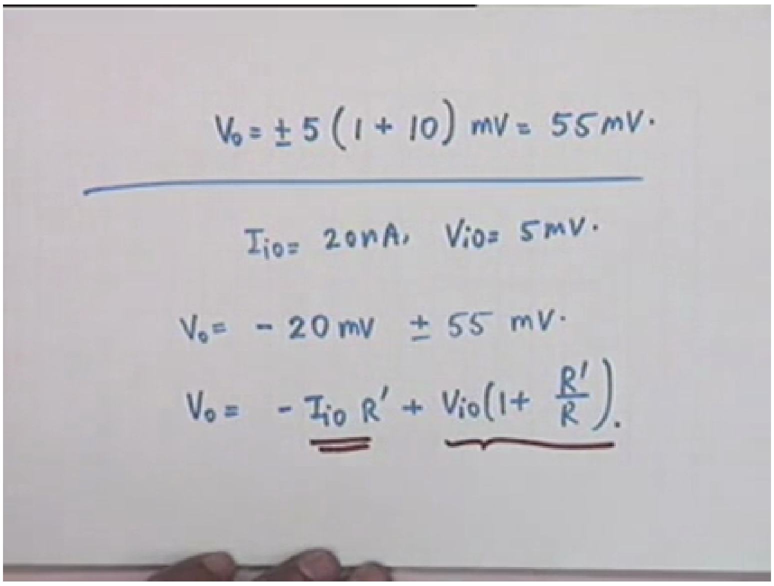

In other words under this condition V0 would be equal to 5 millivolt, then 1+ the gain is 10 and this offset, we have not assumed the polarity, so it could be either positive or negative, so we have plus minus so many millivolts, which is obviously 55 millivolts. What was the value for offset current of 20 nanoamp, what is the value of the voltage?

20 millivolts.

20 millivolts, so this is comparable. Alright, suppose both are present now, suppose I I 0 is equal to 20 nanoamp and VI0 is equal to 5 milliamp, then under this condition what would be V0? V0 would be the superposition of the 2, - 20 millivolts, okay, plus -55 millivolts, right. Or any combination of them, this could also be plus minus. But I want you to notice one thing that V0, if I write the equation minus I I 0 R prime less VI0 1+ R prime by R, please follow carefully, this is how we calculated by superposition. Now you notice that as far as gain is concerned, all that matters is this ratio, R prime by R, is not that right. Changing R prime and R, that is scaling the resistances, instead of 1 meg, let say we make it 0.5 meg, then instead of 100 K we have to make it 50 K, that does not change the offset output due to input offset voltage but it definitely changes due to the current.

Is not that right and therefore reduce the current offset, the lower the value of the resistance the better. Is the point clear? Scaling the resistance, you see this is proportional to R prime, so if R prime is reduced by a factor of 2, the contribution to the output offset voltage will be input offset current reduced by the factor 2. But it does not change the leakage of the offset voltage.

But it may not be always true, the current offset power is going against the voltage offset power.

Okay, the magnitude, the magnitude changes, it reduces. So the worst-case, worst-case would be 55 and 20, -75 or +75. But you see the contribution, contribution to do I I 0 decreases if the resistances are scaled down, this is the important point. Where is the contribution, the input offset voltage does not change because it depends on the ratio, okay. Now if there is an offset, if there is an offset let us say, let us take this particular case 20 nanoamp and 5 millivolts. And your signal itself is let us say pickup from a sensor, maybe a vibration sensor which picks up singles of the order of 1 millivolt.

Then your offset is going to offset everything, is not that right? It is superimposed on the output voltage of 75 millivolt, okay and you will be nowhere, the signal itself would be shifted and this is, there is a DC level and therefore further processing will become a problem, all right. So what one does is if this is an offset, and it is a very sophisticated application where the signal level that is picked up is very very small, you have to balance the offset. And this balancing is done by connecting a small voltage source to one of the terminal, all right. And let me show you the circuit.

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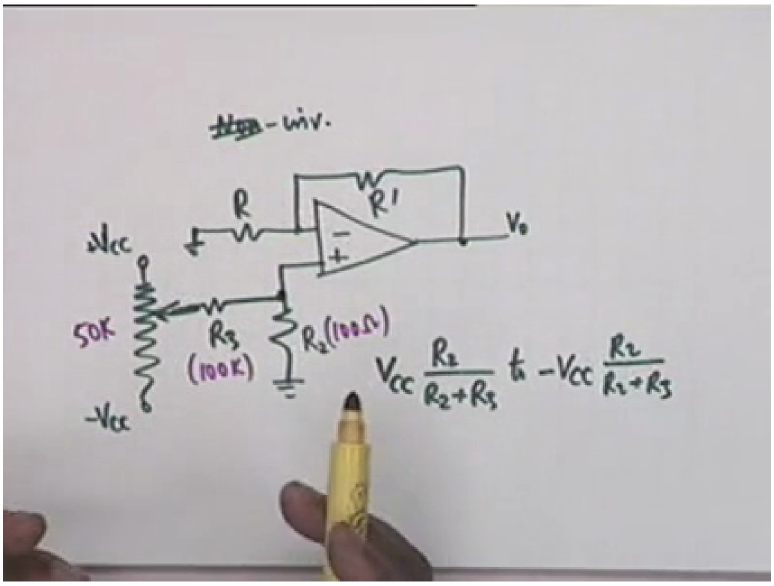

If you are interested is a noninverting amplifier, then the balancing circuit is applied to the non-, I am sorry if you are interested in the inverting amplifier, then the voltage, the additional DC voltage connected to the noninverting terminal. For example you have an inverting amplifier like this, R prime and R to this point is attached small voltage source and this voltage is made adjustable so that you can exactly, exactly offset the effect of offset, all right. So that you can make V0 equal to 0 under no signal condition and this is done like this.

You connect a resistance R2 here, I will show the typical values later, another resistance R3 and then a potentiometer, the ends of which are connected to VCC, plus VCC and minus VCC. Suppose these are okay plus VCC and minus VCC, the potentiometer comes here, okay. So the voltage that you can apply here shall range from plus VCC, R2 by R2 plus R3, that is the maximum that you can get to what is the minimum that you can get, minus VCC multiplied by R2 by R2 plus R3.

And any offset, whether it is due to current or due to voltage, all you need is, I do not care what happens here, all I need is that there is no signal, when this terminal is grounded, I must have 0 voltage here, right. So you adjust this and you make it equal to 0, this could be a positive voltage or could be and negative voltage depending on the polarity of I I 0 and VI0, all right. The typical values are, this is a 50 K pot, please remember that these are all to be connected outside, okay. This potentiometer, typically 50 K, R3 Typically is 100 K and R2 typically 100 ohms.

Obviously, obviously the resistance from here to ground cannot be maintained at R parallel R prime, that is required for compensation of offset. Even if the 2 biasing currents are equal, there would appear an offset voltage and we require that. Now since you are applying an external voltage, we do not care, we will, we will make, will make V0 equal to 0 by what is called a brute forcing, brute force technique, okay. We will apply a voltage and you see this is required in very sophisticated applications and in any measurement application for example, the 1st thing that you do is to make an initial adjustment.

There would be an adjustment on the instrument which says offset adjustment. You have to change this, connect the input terminal to ground, you will have to change the potentiometer till the output voltage is 0, okay and then you apply your measurement technique. If the application is that of a noninverting amplifier, obviously all these arrangements will have to make, will have to be connected to the end of R, is the point clear. And the input is applied at the noninverting terminal, agreed. We will continue this discussion tomorrow.