Basic Electronics

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Lecture - 40
Op-amp nonidealities (continued)

Welcome back to Basic Electronics. In this lecture, we will continue with the input bias current of an op-amp and look at its effect on inverting and non-inverting amplifiers and also on the indicator. Next, we will start with a new topic namely op-amp filters. To begin with, we will see what is meant by a filter; what are the various types of filters and how to represent a filter with a transfer function. Let us begin.

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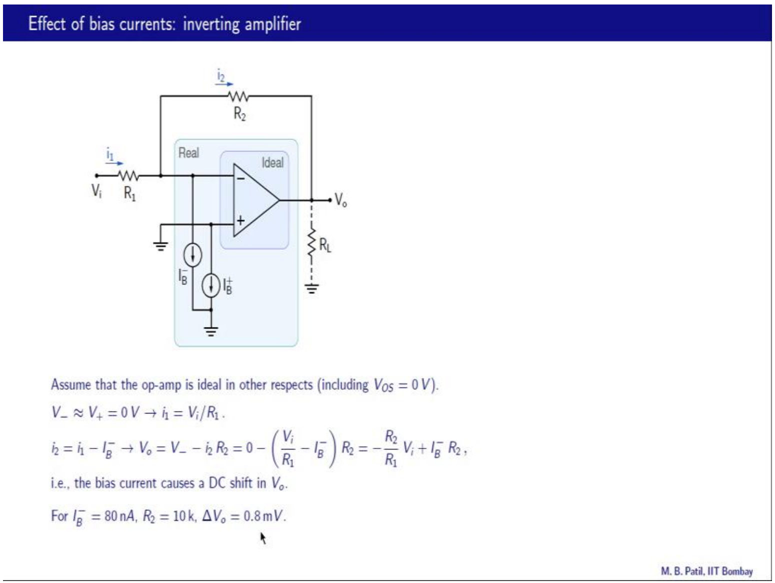

Let us consider the effect of bias currents on the inverting amplifier now. So, we replace the op-amp with the real op-amp model, which includes the bias currents. And, now let us see what V o should be in this case. We will assume that the op-amp is ideal in other respects; that means, we will say that the offset voltage is 0 volts. We have already considered the effect of the offset voltage on the inverting amplifier. And, we will not repeat that here.

So to begin with, since this is the ideal op-amp, V plus and V minus are the same. V plus is 0. And therefore, V minus is also 0. And, if V minus is zero, this current R 1 is

V i minus 0 divided by R 1; that is, V i by R 1. Now, i 2 is not equal to i 1 in this case because we have i B minus going there.

This current is still zero because that is an input current for this ideal op-amp. So, therefore i 2 is i 1 minus i B minus; that equation. And, now we can write in the equation for V o; V o is V minus, which is 0, minus i 2 times R 2. And, we already know i 2. It is i 1 minus i B minus. i 1 is V i by R 1. So, we put it all together. And then, we get minus R 2 by R 1 times V R plus i B minus times R 2. The first term, minus R 2 by R 1 times V i is simply the output voltage we expect from the inverting amplifier. And, the second term arises because of the bias currents.

Now, i B minus is a constant, R 2 is a constant. So, therefore this term represents a DC shift in the output voltage. Let us see how large it is. Take an example i B minus equal to 80 nano amperes, R 2 equal to 10 k. So, i B minus times R 2 is 80 times 10; 800 nano times kilo; that is micro. So, we have 800 micro volts, the same as 0.8 millivolts. So, that is the DC shift we will expect in the output voltage, in this example.

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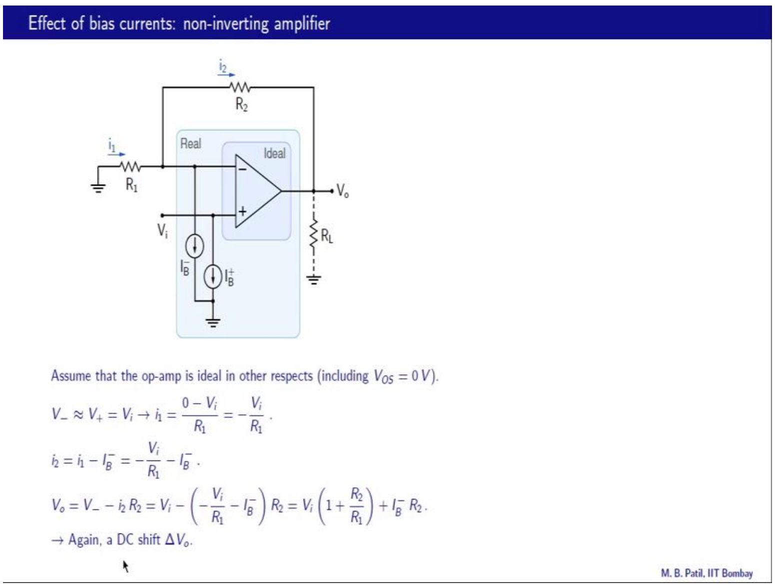

Let us now look at the effect of bias currents on a non-inverting amplifier. To begin with, we replace the op-amp with this model which includes the bias currents. And, we will assume that the op-amp is ideal in other respects, including V o s equal to 0.

Now, since this op-amp is ideal; V minus and V plus are equal. V plus is equal to V i, the input voltage. Therefore, V minus is also equal to V i. And the current i 1, therefore is 0 minus V i divided by R 1, that is, minus V i by R 1. This current i 2 is i 1 minus i B minus because this current is 0. That is an input current for the ideal op-amp. And therefore, we get i 2 equal to minus V i by R 1 minus i B minus. And, now we can write V o as V minus minus this voltage drop, which is i 2 times R 2. Substitute for i 2 from there. And, we finally arrive at V i times 1 plus R 2 by R 1 plus i B minus times R 2. Now, this part is the output voltage we expect from a non-inverting amplifier. And, this is the effect of the bias currents.

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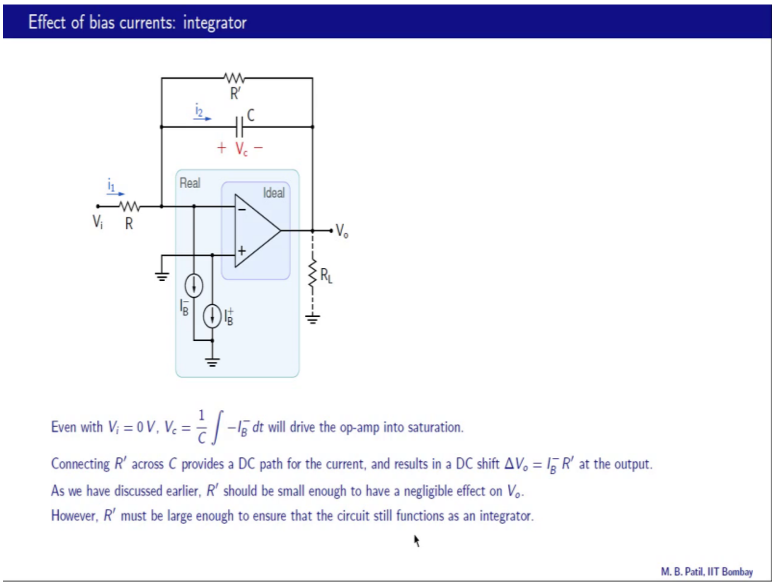

Now i B minus is a constant, R 2 is a constant. So, therefore this term is simply a constant or DC shift in the output voltage. Next, let us look at the integrator and see how it is affected by the bias currents. First, we replace the op-amp with this model which includes the bias currents.

Let us look at the output voltage with the condition that V i is 0. So, this is 0 volts. Now, this is an ideal op-amp with V plus equal to 0. So, therefore V minus is also equal to 0. Now, this register has got this node at 0, this node also at 0. So, therefore i 1 would be 0 and i 2 then would be equal to minus i B minus.

In other words, a constant current will now flow through the capacitor and that will drive the op-amp into saturation. That is the situation we definitely do not want. What is the remedy for this situation? The same as what we saw for the offset voltage problem. And that is to connect a register R prime across the capacitor, and that provides a DC path. So, the current would now flow like that. And, the output voltage will now be V minus, which is 0 plus this voltage drop; which is, i B minus times R prime. So, our V o will now have a shift equal to i B minus times R prime and the op-amp will not go into saturation. As we have discussed earlier, R prime should be small enough to have a negligible effect on V o; that means, we want this delta V o to be small.

At the same time, R prime must be large enough to ensure that the circuit will still function as an integrator. And, we have commented on this point when we were discussing offset voltage and its effect on the integrator.

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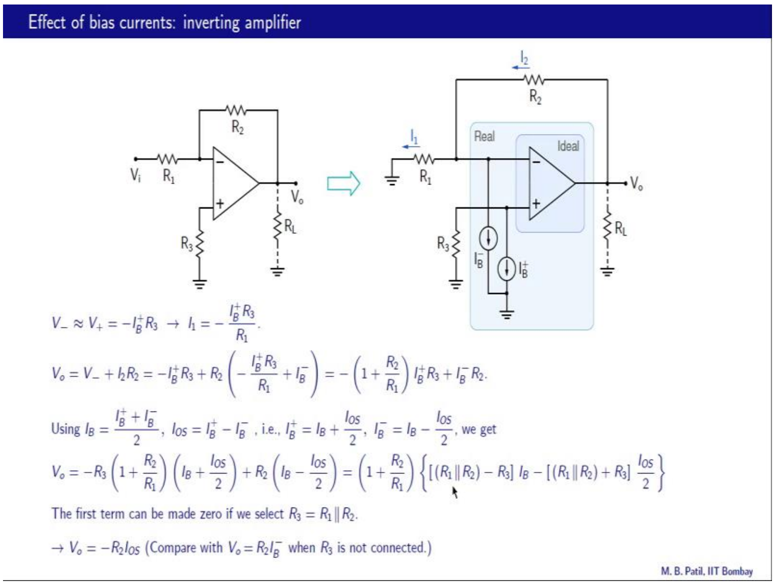

Let us now see how the inverting amplifier circuit can be modified to reduce the effect of the bias currents. And if you recall; what is the effect of bias currents on the inverting amplifier, it was to cause a shift, a DC shift, in the output voltage. So, the modification we consider is adding a resistance R 3 here, between the non-inverting input and ground.

And, let us see how that affects the output voltage. So, first we replace the op-amp with this model, which includes the bias currents. And, now let us analyze this circuit. And, notice that since we are interested only in the effect of bias currents on the output voltage, we have deactivated V i; that means, we have connected this node to ground here.

So, we will analyze this circuit with that condition. Let us start with V plus. This current is zero because has the input current for the ideal op-amp. So, therefore, this i B plus would go like that and the voltage at this node, therefore is minus i B plus times R 3. And, since this op-amp is ideal, V minus and V plus are the same. Therefore, V minus is also equal to minus i B plus times R 3. And, now we can get this current; V minus divided by R 1. So, i 1 turns out to be minus i B plus times R 3 divided by R 1. What about i 2? i 2 is i 1 plus i B minus. And, now we can write an expression for V o. V o is V minus plus this voltage drop. So, that is what we have here; V minus plus i 2 R 2. We already know V minus from there; i 2 is i 1, which is this quantity plus i B minus.

So, all that can be written as this expression here; minus 1 plus R 2 by R 1 times i B plus times R 3 plus i B minus times R 2. Let us now rewrite this expression for V o, in terms of i b; which is, i B plus i B minus by 2. We have seen this definition earlier. That is the average of these two currents. And, i o is which is the offset bias current, which is the difference between i B plus and i B minus. And from these equations, we obtain i B plus as i B plus i o s by 2 and i B minus as i B minus i o s by 2. Now, we can substitute these expressions here. And then, we get all of that which can be rewritten in this form. Now, in this equation we have this 1 plus R 2 by R 1 outside the curly brackets. And within the brackets, we have two terms; one involving i B and the other involving i o s by 2.

And, now what we can do is to take advantage of this minus sign here. Choose R 3 to be equal to R 1 parallel R 2, in which case this entire first term will vanish. And that will surely lead to a much smaller output voltage. Let us see what that is. So, with that substitution R 3 equal to R 1 parallel R 2, over here, as well as over here, we can simplify this V o further. And that turns out to be minus R 2 times i o s. And if you recall, i o s is the offset current and that is much smaller than i b. And therefore, this voltage is a smaller DC shift as compared to R 2 times i B minus, which we obtained when R 3 was 0 or R 3 was not connected. We had connected directly the non-inverting input to the ground.

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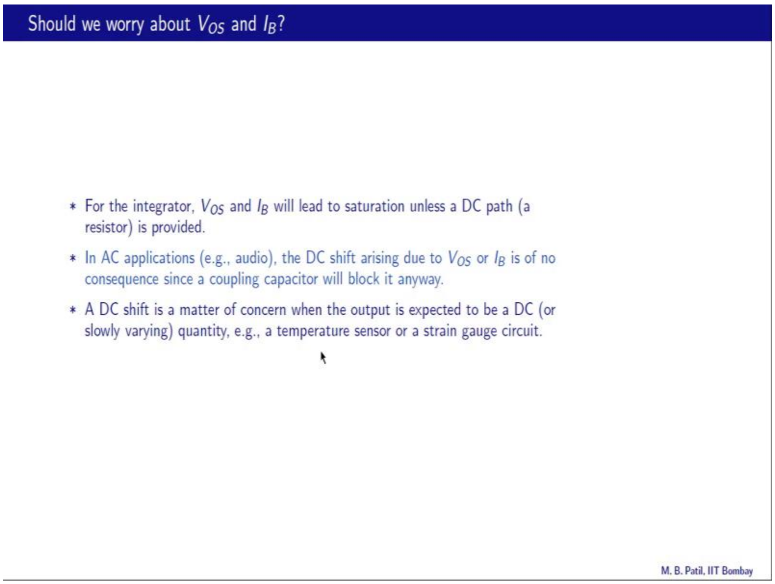

So, this is one trick that you will often see implemented in op-amp circuits, especially when the DC shift of the output is concerned. So, we have looked at the effect of the offset voltage and also the bias currents on several circuits; inverting amplifier, non-inverting amplifier and the integrator. And, the question that arises is, is it really a matter of concern; should not worry about it at all.

Let us look at that question. For the integrator, we have seen that V o s and i B will lead to saturation. And that, of course is disastrous and that has to be corrected. And, how did we correct that? We provided a DC path, a register in parallel with the capacitor and that solved this problem. So that only gives us a DC shift, and did not cause the op-amp to go into saturation.

And what about the inverting and non-inverting amplifiers: it depends on the application. Let us see in what way in AC applications, where the signals are varying with time. For example, audio signals. The DC shift arising due to the offset voltage or the bias current is really of no consequence because in such circuits, there will be coupling capacitors to couple the various stages. And, these coupling capacitors will just block that DC shift delta V o, so that DC shift really will not have any effect on the output. So, in these situations we really do not need to worry about the effect of the offset voltage or the bias currents.

A DC shift is a matter of concern when the output is expected to be DC or slowly varying. For example, consider a temperatures sensor. So, we have something like a bridge circuit to sense the temperature that gets amplified, maybe in one or two stages. And finally, displayed or supplied to some control circuitry. Now, in these situations a DC shift is definitely a matter of concern, which arises because of V o s and i B because that is going to lead to a wrong temperature value being interpreted. So, in these situations definitely we must worry about the offset voltage as well as the bias currents. And, we should try to minimize the effect, either by choosing an op-amp which has much better values of these parameters or by using some circuit tricks.

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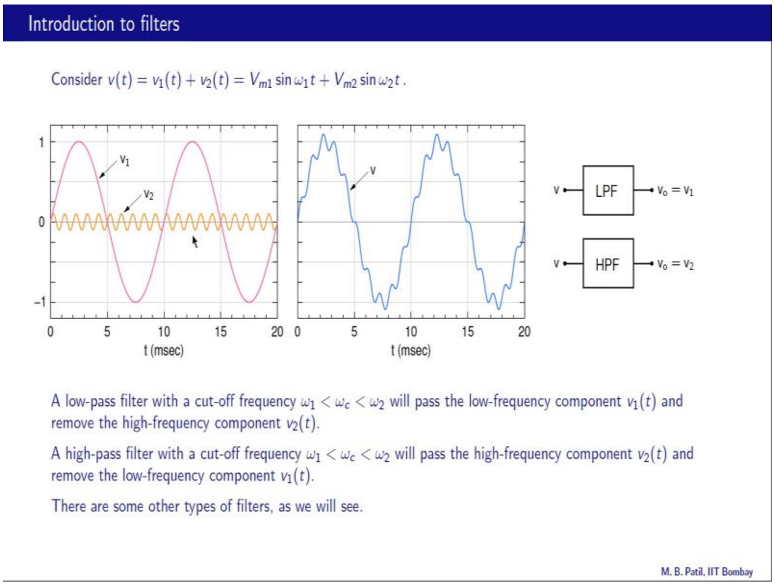

Let us now talk about filters, a very important class of electronic circuits. And, they find applications in many different areas. What we will do is first look at what a filter does, what its functionality is and then we will see how it can be implemented. So, let us take this simple example, where we have V of t as a sum of two components V 1 and V 2. Each of them is a sinusoid. V 1 is V m 1 sin omega 1 t; V 2 is V m 2 sin omega 2 t. This is our V 1, it has a lower frequency and this is our V 2. So, V of t, which is the sum of these two wave forms, looks like this.

And, now what we want to do is to pass this resulting wave form through a filter and see what we get at the output of the filter. Now, let us look at the action of a low-pass filter on this wave form. And before we do that, let us look at the transfer function of a low-pass filter; that means the ratio of the output to the input of the low-pass filter.

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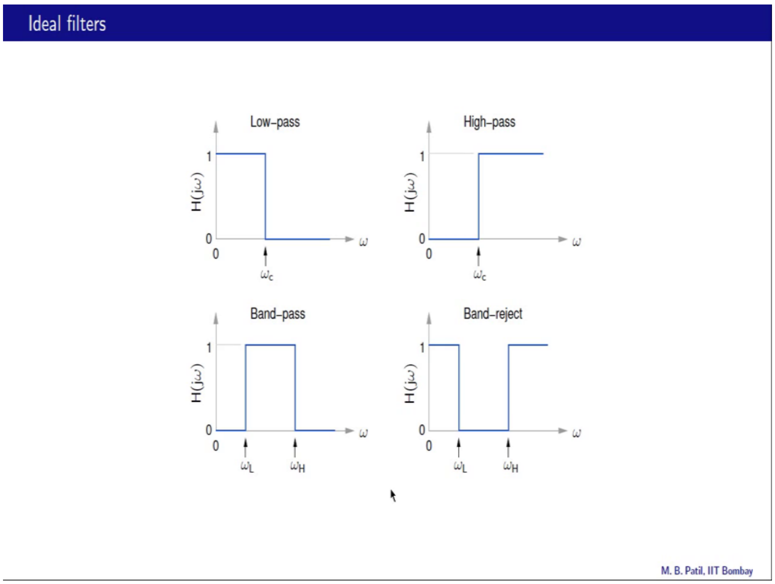

And that is given by this graph here. This is the transfer function of the low-pass filter. This axis is the angular frequency in radiance per second. If omega is less than this cutoff frequency omega c, then the transfer function is 1; that means, the low-pass filter passes all frequencies up to this frequency. If omega is greater than omega c, then the transfer function is 0; that means, the low-pass filter rejects or blocks frequencies higher than omega c.

Now, our input voltage; each composed of two frequencies; this low frequency and this high frequency. And, if we choose the cutoff frequency of the low-pass filter to be somewhere in between these two frequencies, then what will happen is this high frequency component will get rejected and only the low frequency component will get passed. And therefore, at the output we will have V o equal to V 1. That is the low frequency component.

For a high-pass filter, the situation is exactly the opposite. For omega greater than omega c, the transfer function is 1. And therefore, these frequencies will get passed; for omega less than omega c, the transfer function is 0. And therefore, these low frequencies will get rejected. So, let us see what happens when this same input voltage is now applied to a high-pass filter. And, let us say that we choose the cut off frequency of the high-pass filter to be between these two frequencies. Then, what happens is the high frequency gets passed and the low frequency gets rejected. And therefore, at the output of the high-pass filter we have V o equal to V 2. That is, the high frequency component.

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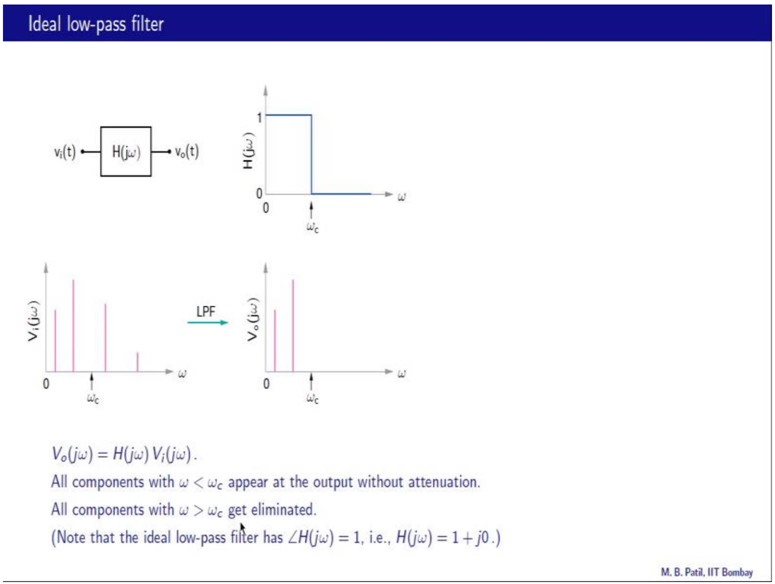

Now, there are some other types of filters as well. And, we will be looking at these very soon. Let us now look at how a low-pass filter is represented. In particular, we will look at ideal low-pass filter first. The transfer function of an ideal low-pass filter looks like this; H of j omega is 1, up to omega c. And, beyond that it is 0. And, the output of the filter is given by in the frequency domain H of j omega times V i of j omega. Here is an example. Let us say our input voltage has various frequency components or Fourier components; one, two, three, four components. And, these components will have different values or amplitudes. Now, if we pass this through a low-pass filter with cutoff frequency omega c located here, then it will pass these two components. But, block these two because these two will get multiplied by 0, these two will get multiplied by 1.

So, our resulting output in the frequency domain will look like this, where the high frequency components have been eliminated. So, all components with omega less than omega c appear at the output without attenuation. And, all components with omega greater than omega c get eliminated. And, how do we express mathematically this H of j omega for this ideal low-pass filter? It is simply 1 for frequencies up to omega c, and that 1 is the real number 1. So, we can write that as 1 plus j 0. And, ideal high-pass filter does just the opposite. So, it is H of j omega is 1 for all frequencies higher than omega c. And, it is zero for all frequencies, which are lower than omega c. So, it passes high frequencies. That is why it is called high-pass and blocks low frequencies.

Here is a filter called the band-pass filter. So, it passes a band of frequencies between omega l and omega h. So, between these two frequencies its value is 1. And, otherwise it is 0. Here is a band reject filter. In other words, it rejects all frequencies which are in a specific band given by omega l and omega h. So, its transfer function is 0 in this band. And it is 1, otherwise; now that all of these are ideal filters. In real life, we would not be able to implement filters with exactly these transfer functions. So, we can approximate these transfer functions with certain mathematical expressions and then realize those with circuits.

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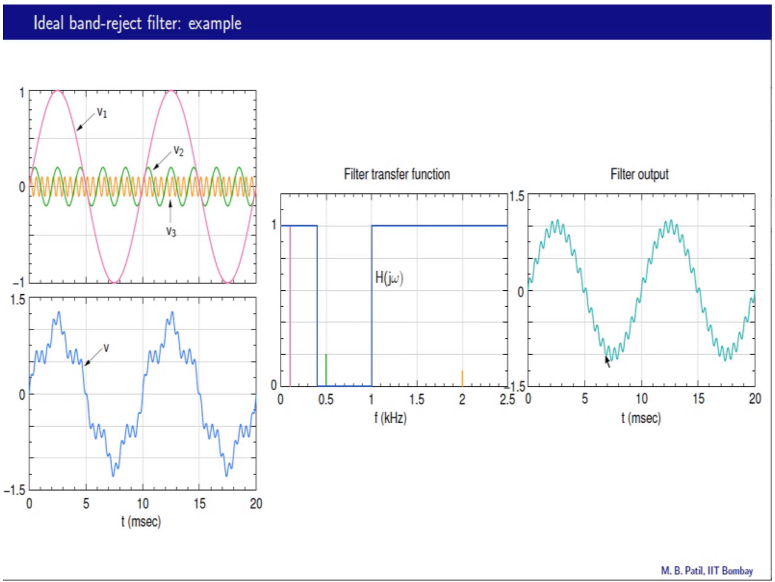

Let us now look at the effect of ideal filters on a sample wave form. The wave form that we consider is this; V of t. It has three frequency components; V 1, V 2 and V 3. V 1 has a frequency of 0.1 kilo hertz and an amplitude of 1, V 2 has a frequency of 0.5 kilo hertz and an amplitude of 0.2 and V 3 has a frequency of 2 kilo hertz and an amplitude of 0.1. So, we are passing V of t through our low-pass filter, to start with, which has a transfer function given by this plot here. And, the cut off frequency of that filter is 0.4 kilo hertz. So, all frequencies up to 0.4 kilohertz will get passed and all higher frequencies will get blocked. So, what happens? This component gets multiplied by 1, these get multiplied by 0. And therefore, only this one survives. And, there therefore you see V 1 of t at the output of the filter as shown here.

If we pass the same V of t through a high-pass filter now with this transfer function here, then only the high frequency component survives. These two get eliminated. And then, at the output we have the voltage corresponding to this component; that is, V 3 as shown here.

What about a band-pass filter? Here is an example. So, the transfer function is 1, here between these two frequencies. And, it is 0, otherwise. Now, only this component which lies in this band will go through. And, these two will get eliminated. And therefore, we have the green one; that is, V 2 of t as shown here. Similarly, if we pass V of t through a band reject filter which has a transfer function shown here, then this component gets eliminated. This low frequency component and this high frequency component go through. And, what we get at the output is the combination of this V 1 and V 3. And that looks like this.

To summarize, we have completed our discussion on input bias currents of an op-amp and started a new topic namely; op-amp filters. We have looked at how a filter can be represented with the transfer function H of j omega. In the next class, we will look at the use of (Refer Time: 27:31) to show how a given transfer function varies with frequency. That is all for now. See you next time.