INDIAN INSTITUTE OF SCIENCE, BANGALORE

Electronic Modules for Industrial Applications using Op-Amps

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Welcome to this module, and this is in-continuation with our last module regarding understanding the op-amps, the idea of this particular modules is to summarize what are the parameters, characteristics of an operation amplifier.

And here now we will see filters and oscillators, because we will be implementing this particular theory that we are understanding in this modules into various circuits, so let's see what we are learning in this particular module.

To start with we'll start with filters, so when you talk about filters, filters are what? They are circuits that are capable of passing certain signal and blocking another,
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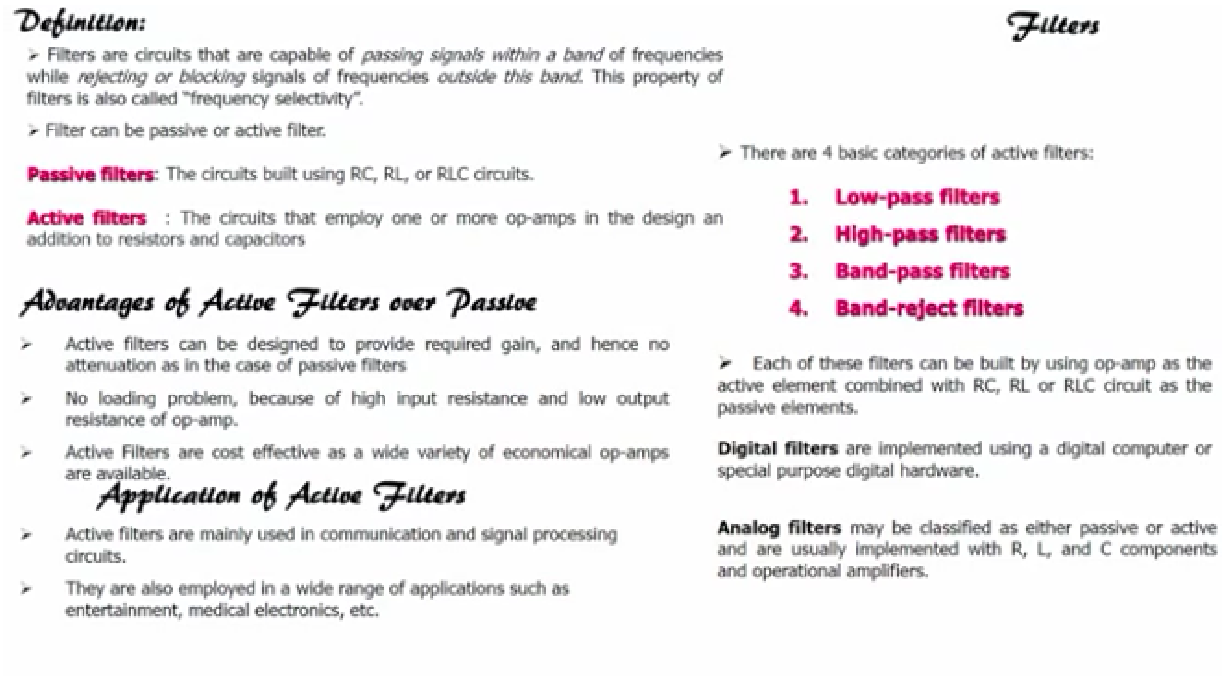

so what do you mean by passing certain signals? The band of frequencies that you want to pass, we can design a circuit that will allow to pass those band of frequencies, our desired band of frequencies, while blocking the undesired signals alright, so this property of the filters is called frequency selectivity.

Now if you divide the filters, filters can be active filters, and filter can be passive filters, so what do you mean by passive filters? Passive filters are filters that use RC, that is resistor in capacitor, resistor in inductor or all combinations of resistor, capacitor or inductor, all three combinations, while active components or active filters are the one that employs Op-Amp in addition to resistors and capacitors, alright.

Now what are the advantages of active filters over passive filters, so active filters can design or can be designed to provide gain and hence no attenuation as in case of passive filters, we have seen that in the earlier course, same way there is no loading problem and active filters are cost effective.

What are the applications? Applications are it is used in communication and signal processing circuits, there also employed the wide range of applications such as entertainment and medical electronics, of course there are lot of applications that’s why we have written etcetera.

Now four basic categories of active filters, low-pass, high-pass, band-pass and band-reject, right, and further we can also classify active filters into digital filters and analog filters, so digital filters are implemented using a digital computer or special purpose digital hardware, while analog filters can be classified as either active or passive implemented with R, L and C as well as op-amps.

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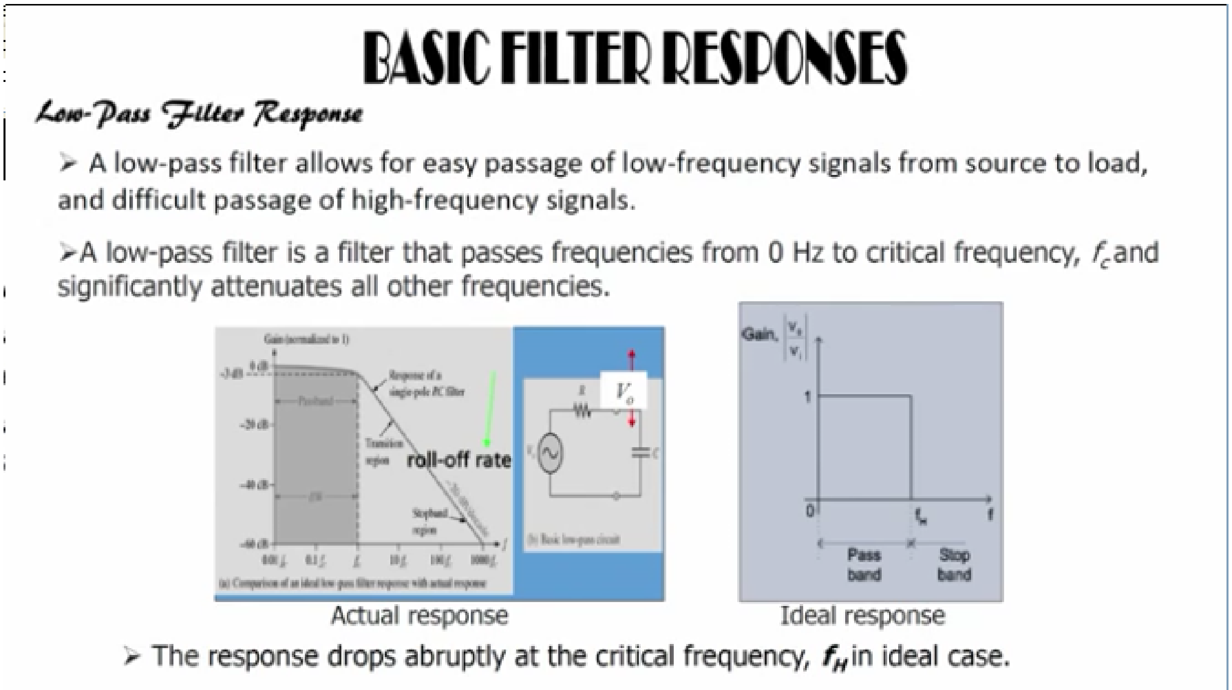

So we have then seen each of those filters which are low-pass, high-pass, band-pass, band-reject, so let us see once again low-pass filter, what are low-pass filter? Low-pass filter allows for easy passage of low frequency signals from source to load, and difficult passage of high-frequency signals, so now if you see reserve kit actual response would be ideal response if you see at the right side, and actual response is on the left side, so when you see ideal response right, it's like a brick, like a brick wall, for actual response is little bit different than ideal response and here one new definition comes into picture is called roll-off rate, roll-off rate alright.

So a low-pass filter is a filter that passes frequency from 0 hertz to critical frequency, what is a critical frequency? Frequency at which we want to stop the, or frequency until which we want to pass the signal in case of low-pass filter, so FC here is the frequency cut-off frequency or critical frequency above which we don't want the signals to pass, and that's why you see that after FC in the left side graph, actual response plot, you see that after a FC the signal starts attenuating, right, okay.

What other bands we can see? We can see a pass-band, right, then here we see this is your bandwidth, this is your transition region, this is your response of signal pole RC filter, single pole is when there is 1R and 1C, here you can see 1R and 1C, right, so roll-off rate, roll-off rate is about -20DB per decade and then there is a stop-band, alright, so the Y axis is gain, X axis is your frequency, alright.
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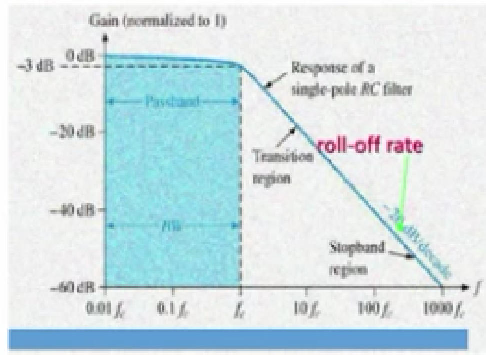
Passband of a filter is the range of frequencies that are allowed to pass through the filter with minimum attenuation (usually defined as less than -3 dB of attenuation).

Transition region shows the area where the fall-off occurs.



Stopband is the range of frequencies that have the most attenuation.

Critical frequency, f_c, (also called the cutoff frequency) defines the end of the passband and normally specified at the point where the response drops –3 dB (70.7%) from the passband response.

Now pass-band, what is pass-band? Pass-band, this pass-band is the range of frequencies that are allowed to pass through the filter with minimum attenuation, while transition region you can see a transition region it shows the area where the fall-off occurs, now so from here after the pass-band is over the fall-off starts, the attenuation starts and this is your transition region.

Then there is stop-band, right, is the range of frequency that have most attenuation, finally that they are critical frequency FC, right, also call cut off frequency as we have, as I have just described in the last slide, and it defines the end of pass band and normally specified the point where the response drops so -3DB of 70.7% from the pass-band response, right, so that is your critical frequency FC, okay.

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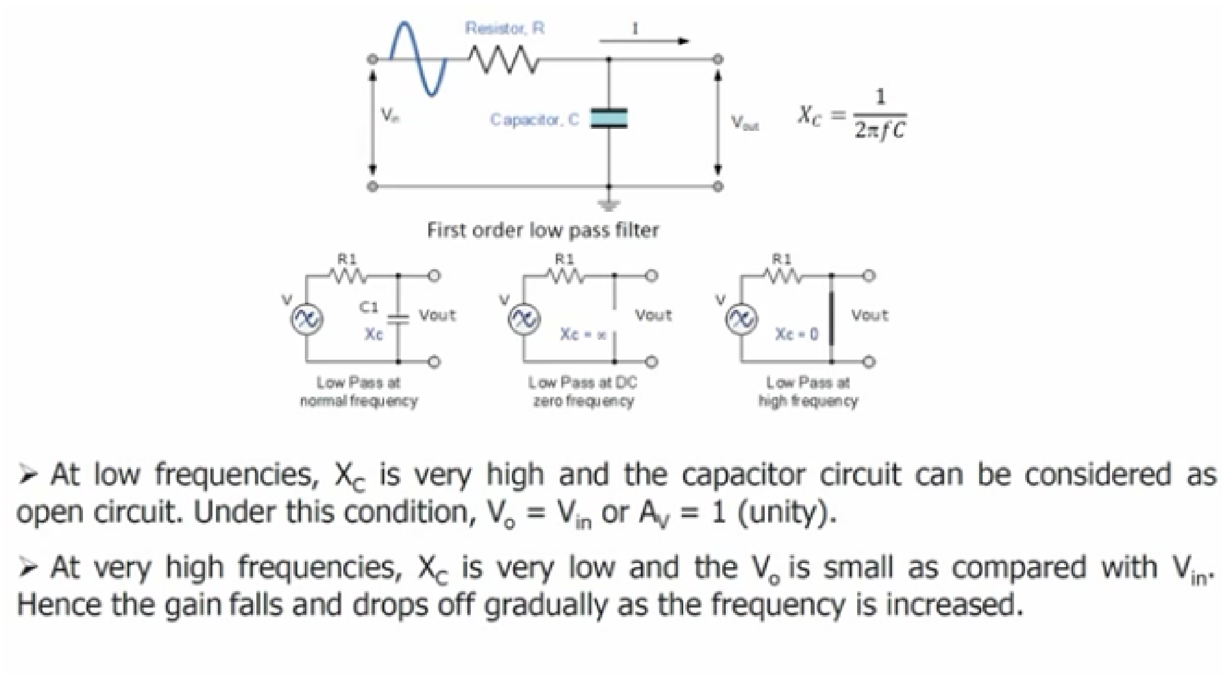

Now when you want to design a low-pass filter, first order low-pass filter resistor comes at the starting and then there is a capacitor, so signal pass through the resistor and capacitor in this particular fashion, so if I have XC, XC is nothing but 1/2 pi FC, right, so in the low-pass at normal frequency what will happen? At low frequency your XC, right, XC would be very high and the capacitor circuit can be consider as an open circuit.

So here if you see in the center, right, this one in this case if your frequency is low your XC can be consider as open circuit and all the frequency, there is low frequency can pass and we can get the output. If the frequency is high, if frequency is high right then XC would be consider very low, XC would be low right, if F is high XC would be low, if XC is low then VO is small as compare to VIN, hence the gain and drop, falls gradually as a frequency is increased, this is how the RC filter works, right, a lower frequency the circuit allows the signal to pass at higher frequency or the frequency above cut-off frequency the circuit will stop the signal to pass through it.

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➢ The **bandwidth** of an **ideal** low-pass filter is equal to f_c:

$$BW = f_c$$

➢ The critical frequency of a low-pass RC filter occurs when $X_C = R$ and can be calculated using the formula below:

$$f_c = \frac{1}{2\pi RC}$$

So the bandwidth of an ideal low-pass filter, bandwidth of an ideal low-pass filter FC right is equal to bandwidth is equal to FC, whatever the critical frequency we have or cut off frequency we have that is equal to your bandwidth. The critical frequency of a low-pass filter occurs when XC = R, right and it can be calculated using FC = 1/2 pi RC.

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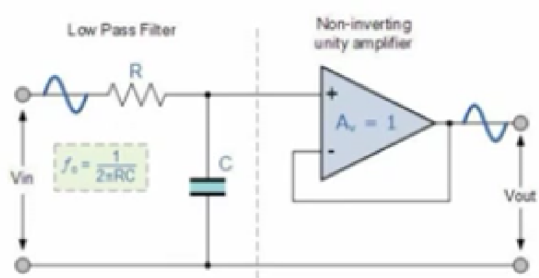
First Order Low Pass Filter



➢ This first-order low pass active filter, consists simply of a passive RC filter stage providing a low frequency path to the input of a non-inverting operational amplifier. The amplifier is configured as a voltage-follower (Buffer) giving it a DC gain of one, Av = +1 or unity gain as opposed to the previous passive RC filter which has a DC gain of less than unity.

➢ The advantage of this configuration is that the op-amps high input impedance prevents excessive loading on the filters output while its low output impedance prevents the filters cut-off frequency point from being affected by changes in the impedance of the load.

➢ While this configuration provides good stability to the filter, its main disadvantage is that it has no voltage gain above one. However, although the voltage gain is unity the power gain is very high as its output impedance is much lower than its input impedance. If a voltage gain greater than one is required we can use the following filter circuit.

So first order low-pass filter if I use active filter, active filter is when you use amplifier, you use Op-Amp, right here we are using Op-Amp, and as you can see Op-Amp is just in a non-inverting configuration and say unity amplifier, unity amplifier right, so the first order low-pass active filter consists of simple passive RC filter, and a low frequency path to the input of a non-inverting operational amplifier, the amplifier is configured as a voltage-follower, unity gain or what do you call? Non-inverting unity gain amplifier, right, where is DC gain = 1, right, DC gain = 1, the advantage of this particular configuration is that the Op-Amp has high input impedance, we have seen Op-Amp input impedance is extremely high, so this prevents excessive loading of filters output, while is low output impedance prevents the filters cut-off frequency point from being affected by the changes in the frequency of the load, right, this advantage of using the operational amplifier as unity gain amplifier or voltage follower, right.

We are refreshing again what we have been learning in the last course and people who have not register for my last course they may see the videos and come up with the understanding about this particular course, so for those people who have not attended by last course we are repeating kind of summarizing the concepts in this modules, alright.

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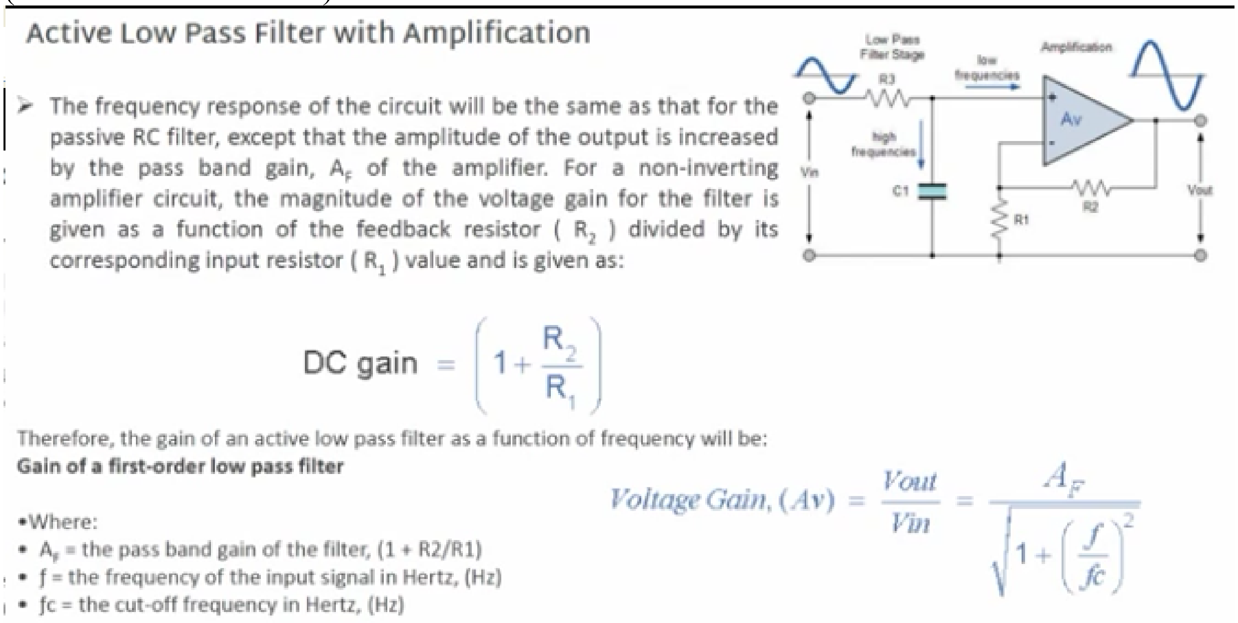

So if I use amplification, if I use amplifier here, right, so the signal is applied to the non-inverting configuration, non-inverting terminal of the Op-Amp, so what is a gain? Gain is DC gain is 1+R2/R1, right, and my voltage gain is nothing but V out/V in which is AF/ under root of 1+F/FC whole square, right which is easy to know, so what happens here? What happens here? For non-inverting amplifier circuit the magnitude of voltage gain right is given as a function of it by resistor by the input resistor, so you have RC filter here at the input stage and then you have a non-inverting amplifier, so here you can amplify the gain you see, the gain or signal can be amplified with the whatever gain you have and you can set the gain with the help of R2 and R1, right, so that’s the advantage.

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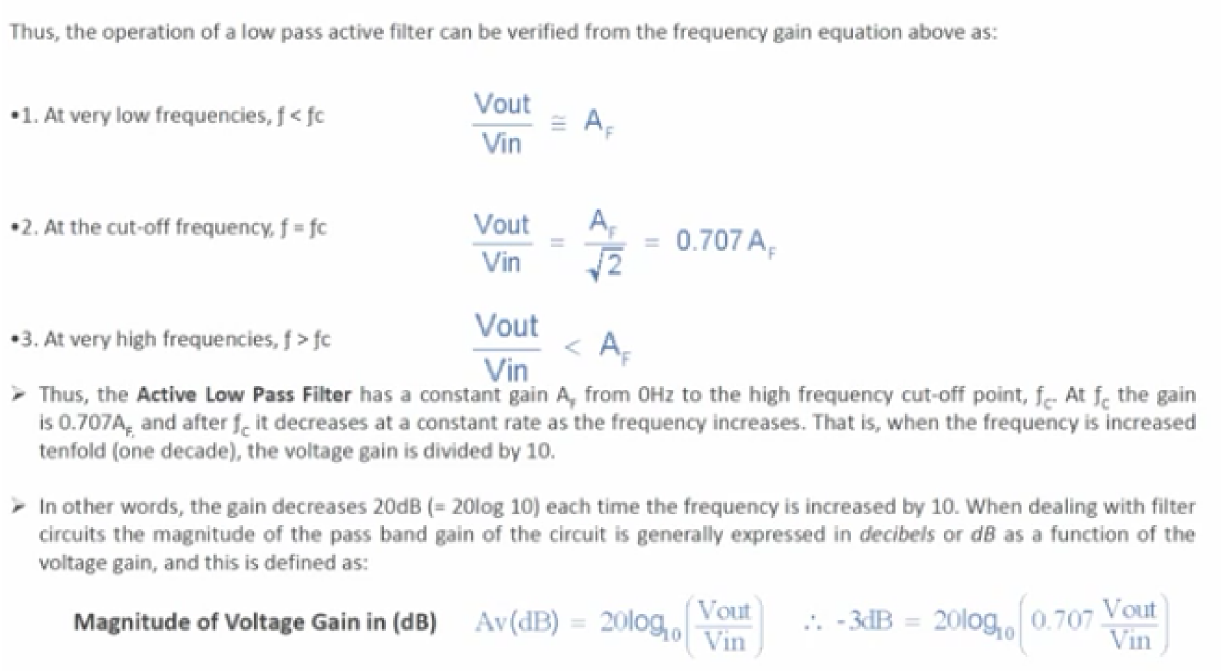

For this configuration that is low-pass active filter we can see that at low frequencies F is less than FC and V out/V in is given by AF. At the cut-off frequency where F = FC V out/V in is given by 0.707 AF, by that higher frequency where F is greater than FC V out/V in is less than AF, right, this will be kind of opposite to the high-pass filter and we will see that, alright, and a magnitude of voltage gain here if it's in DB then 20 log 10 V out/V in, that is -3DB = 20 log 10 0.707 V out/V in, right.

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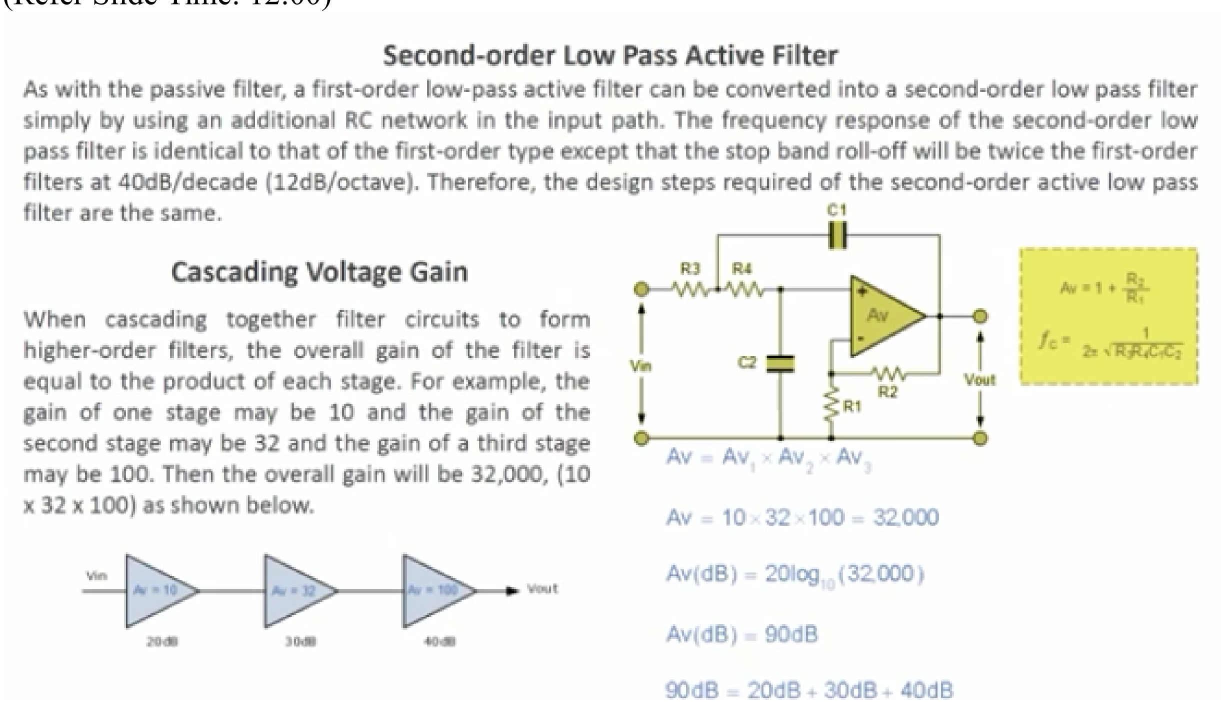

Now if I talk about second order low-pass filter I have 2R and 2C, right, 2R and 2C, here the gain again AV is 1+R2/R1 which you can see here, while FC would be 1/2 pi under root of R3, R4, C1 and C2, right, so in this case if my R3 = R4 and C1 = C2 I'll have FC = 1/2 pi under root of R square C square, so it will be nothing but FC = 1/2 pi RC.

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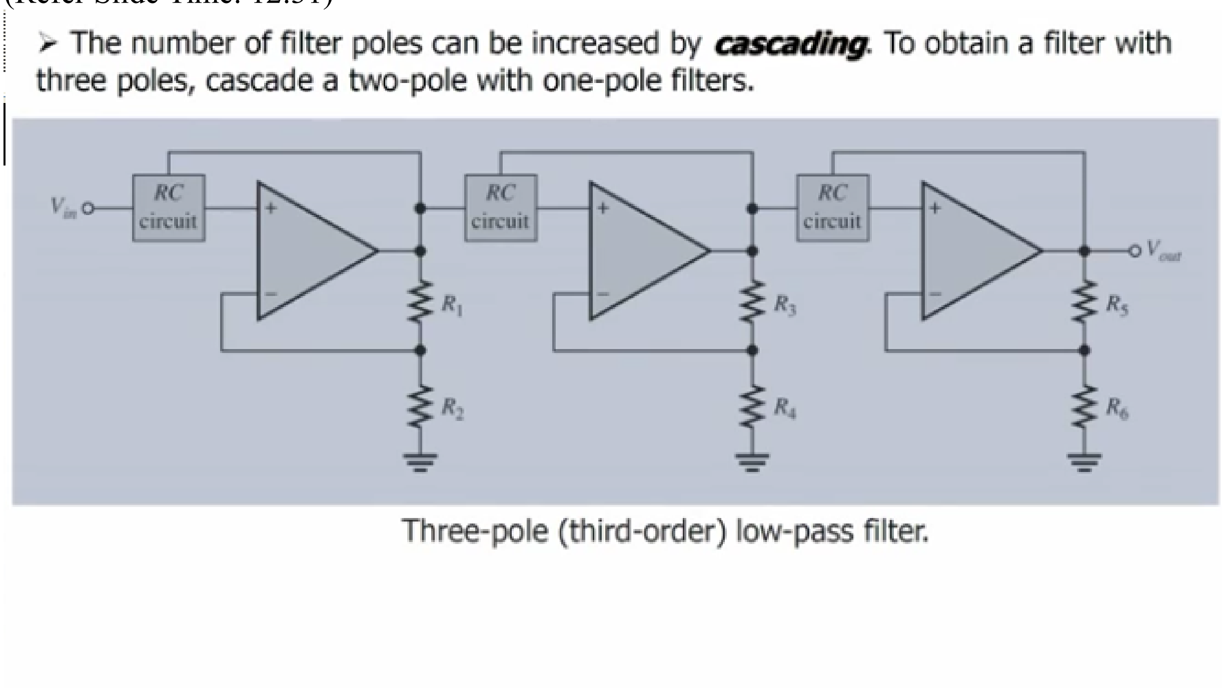

So the cascading from single pole to two pole filter we can make it by cascading the R and C, so if you keep on cascading the number of filter poles can be increased by cascading to obtain a filter with three poles, cascade a two-pole with one pole filters and so on, so this is a three pole filter low-pass filter. One pole will give you -20 DB per decade, right, so three pole will give you about -60DB per decade.

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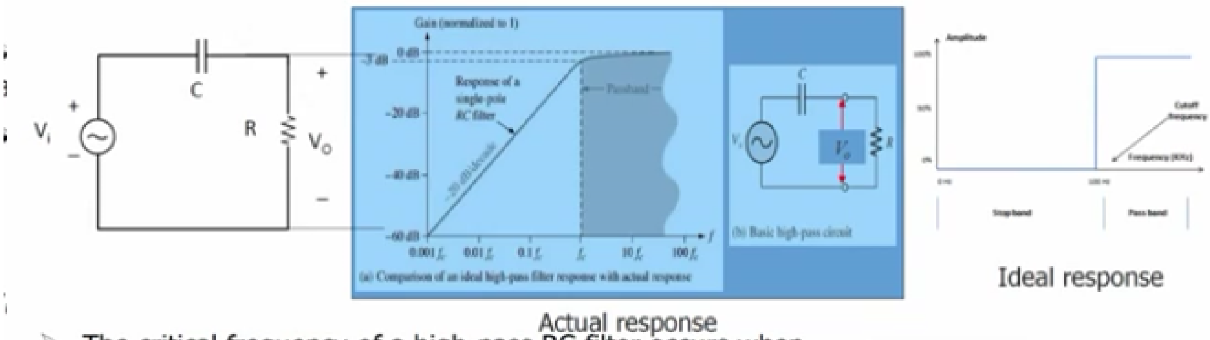
High-Pass Filter Response

- A **high-pass filter** is a filter that significantly attenuates or rejects all frequencies **below** f_c and passes all frequencies **above** f_c.
- The passband of a high-pass filter is all frequencies above the critical frequency.



- The critical frequency of a high-pass RC filter occurs when
- $X_C = R$ and can be calculated using the formula:
- Ideally, the response rises abruptly at the critical frequency, f_c

$$f_c = \frac{1}{2\pi RC}$$

Now if I talk about high-pass filter, what is a change? High-pass filter we have capacitor at the input and then it goes to the resistor, so signal goes to the capacitor and a resistor, right, in this one the high-pass filter will significantly attenuate or reject all frequencies below FC, correct and passes all frequency above FC, so here the plot would be that here that will be attenuation at the input and then as the frequency which is closed to FC and above FC it will start, the signal can pass through the high-pass filter, right, this is ideal response for high pass filter, and again formula remain same FC = 1/2 pi RC.

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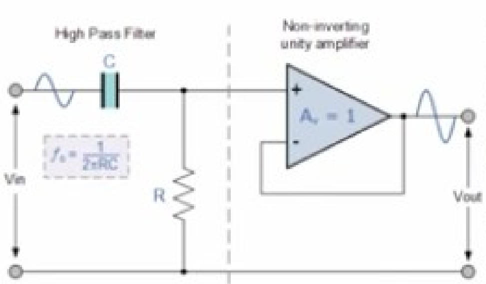
First Order High Pass Filter

Like the previous active low pass filter circuit, the simplest form of an *active high pass filter* is to connect a standard inverting or non-inverting operational amplifier to the basic RC high pass passive filter circuit as shown.



Technically, there is no such thing as an active high pass filter. Unlike Passive High Pass Filters which have an "infinite" frequency response, the maximum pass band frequency response of an active high pass filter is limited by the open-loop characteristics or bandwidth of the operational amplifier being used, making them appear as if they are band pass filters with a high frequency cut-off determined by the selection of op-amp and gain.

So if I want to design a first order high-pass filter right with the operational amplifier, an operational amplifier is unity gain amplifier then here I can again design a high-pass active filter with a non-inverting unity gain amplifier, non-inverting because the signals are applied to the non-inverting terminal, unity gain amplifier we know the circuit, right, so this is how we can create a non-inverting, sorry this is how we can create high-pass active filter.

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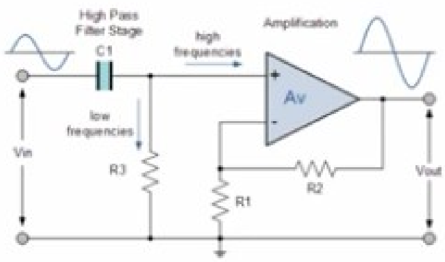
Active High Pass Filter with Amplification

A first-order (single-pole) Active High Pass Filter as its name implies, attenuates low frequencies and passes high frequency signals. It consists simply of a passive filter section followed by a non-inverting operational amplifier. The frequency response of the circuit is the same as that of the passive filter, except that the amplitude of the signal is increased by the gain of the amplifier and for a non-inverting amplifier the value of the pass band voltage gain is given as 1 + R2/R1, the same as for the low pass filter circuit.



This *first-order high pass filter*, consists simply of a passive filter followed by a non-inverting amplifier. The frequency response of the circuit is the same as that of the passive filter, except that the amplitude of the signal is increased by the gain of the amplifier. For a non-inverting amplifier circuit, the magnitude of the voltage gain for the filter is given as a function of the feedback resistor (R2) divided by its corresponding input resistor (R1) value and is given as:

$$\text{Voltage Gain, }(Av) = \frac{Vout}{Vin} = \frac{A_F\left(\frac{f}{fc}\right)}{\sqrt{1+\left(\frac{f}{fc}\right)^2}}$$

Where:

A_F = the Pass band Gain of the filter, (1 + R2/R1)
f = the Frequency of the Input Signal in Hertz, (Hz)
fc = the Cut-off Frequency in Hertz, (Hz)

Now if I want to use amplification factor, amplification factor into the high-pass filter, then what will I do? I will have the Op-Amp in a amplifier configuration as an amplifier, that here you can see the Op-Amp is used as an non-inverting amplifier, so here I can change the gain or amplify the signal based on the gain that I can edge or straight, so whatever I want I can adjust the gain, and how can I do that? By changing the value of R2 and R1, right, because the gain for non-inverting amplifier is 1+R2/R1, the voltage gain here in this case would be AF into 1F/FC divide by 1+F/FC whole square, but what is AF? AF is your pass-band gain, F is the frequency of input signal, and FC is the cut-off frequency in hertz or critical frequency.

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Just like the low pass filter, the operation of a high pass active filter can be verified from the frequency gain equation above as:

1. At very low frequencies, $f < fc$ $$\frac{Vout}{Vin} < A_F$$

2. At the cut-off frequency, $f = fc$ $$\frac{Vout}{Vin} = \frac{A_F}{\sqrt{2}} = 0.707\,A_F$$

3. At very high frequencies, $f > fc$ $$\frac{Vout}{Vin} \cong A_F$$

Then, the **Active High Pass Filter** has a gain A_F that increases from 0Hz to the low frequency cut-off point, f_C at 20dB/decade as the frequency increases. At f_C the gain is $0.707A_F$, and after f_C all frequencies are pass band frequencies so the filter has a constant gain A_F with the highest frequency being determined by the closed loop bandwidth of the op-amp.

So here if you see in case of low-pass filter V out/V in was equal to AF, and V out/V in in case of high frequency was less than AF, right, here is opposite, so here V out/V in less than AF, V out/V in for F = FC is 0.07, and F greater than FC = AF.

So one more thing is that the active filter, the active high-pass filter has a gain AF that increases from 0 hertz to low cut-off frequency like low frequency cut-off point and then FC at 20DB per decade as the frequency increases, F = FC the gain is nothing but 0.707 of AF, and then when F is greater than FC there gain would be nothing but equals to AF.

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Band Pass Filter

- The principal characteristic of a Band Pass Filter or any filter for that matter, is its ability to pass frequencies relatively un-attenuated over a specified band or spread of frequencies called the "Pass Band" and attenuated the other bands of frequency called "Stop Band"
- Simple Band Pass Filter can be easily made by cascading together a single Low Pass Filter with a single High Pass Filter as shown in the Figure below.

- The cut-off or corner frequency of the low pass filter (LPF) is higher than the cut-off frequency of the high pass filter (HPF) and the difference between the frequencies at the -3dB point will determine the "bandwidth" of the band pass filter while attenuating any signals outside of these points

So band-pass filter when you talk about band-pass filter it has a high-pass filter, amplification, and a low-pass filter, now we want to pass a certain band, right, you've seen low-pass filter that it will pass the low frequency band, high pass filter it will pass the high frequency signal, and then we want to fabricate or design a band pass filter it should be combination of high-pass and low-pass filter with amplification if it is an active filter.

So the principal characteristic of band-pass filter or any filter for that matter, is its ability to pass frequencies relatively un-attenuated over a specified band or a spread of frequencies called pass band, right, the cut of frequency or corner frequency of low-pass filter is had then the cut-off frequency of the high-pass filter, right, and the different between the frequency is at -3DB point will determine the bandwidth of the band pass filter, so this is very easy to understand low-pass filter and high-pass filter.

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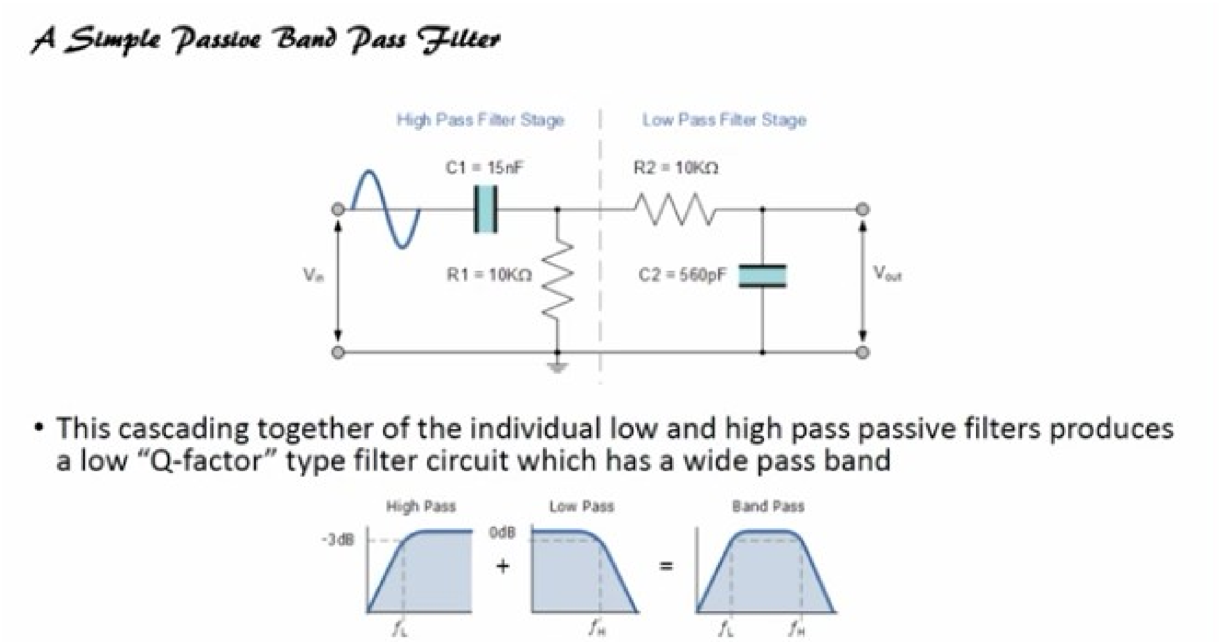

Figure 10

So now if you see here, if you want to fabricate or if you want to design a circuit, if you want to design a circuit right which is band-pass filter and that too is passive then you can use a combination of high-pass filter and low-pass filter, you see the signal from high-pass filter, the signal from low-pass filter, so if you combine both you get a band-pass filter. So cascading together the individual low-pass and high-pass filter produces low Q-factor type filter which has a wide pass band.

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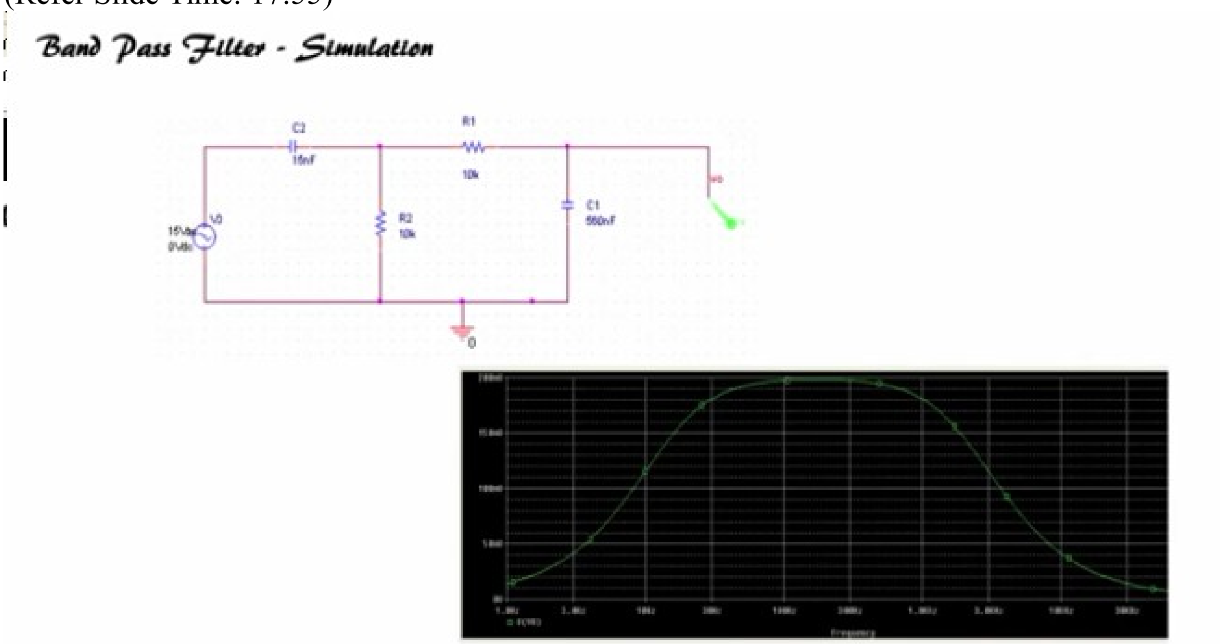

Figure 10 a

It is just a simulation if you want to work on the simulation you can use Simulink, right,

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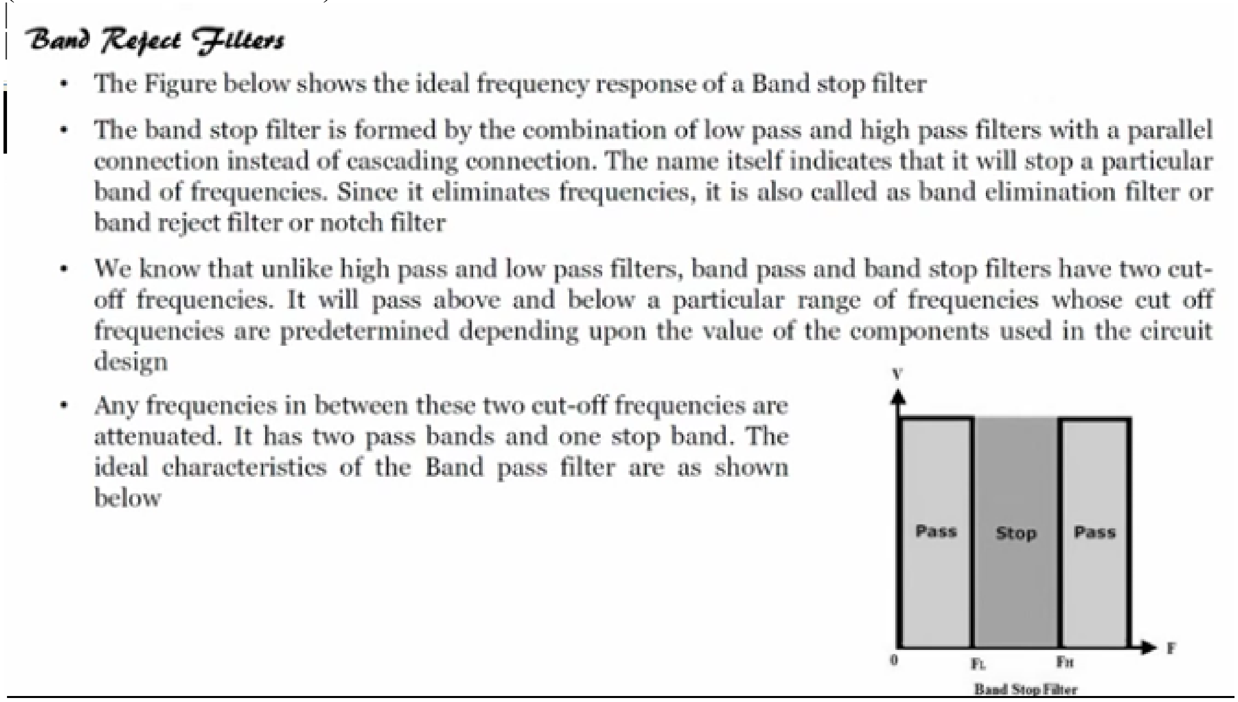

then band reject filter, so as the name suggest it will reject a particular band of frequencies, right, so the figure shows, which figure? Figure here it shows right, this stop band, pass band, and pass band, so it shows the ideal frequency response of band stop filter, this is a band stop filter it’s also called band reject filter, right you can see here, this is the band stop or band reject filter or it is also called notch filter, alright.

So don’t get confused if it is band stop or band reject or notch, everything is same, so band stop filter is formed by combination of low pass and high pass filters with a parallel connection instead of cascading connection, right.

In the case of band pass filter we were cascading the low-pass and high-pass, in case of band reject filter we are again cascading but in a parallel configuration, the name itself suggest that it will stop a particular band of frequencies, right, since it eliminates frequency also called band elimination filter or band reject filter or notch filter, right.

So we know that unlike high-pass and low-pass, band-pass and band stop filters have two cut-off frequency, you can see here FL and FH right, two cut-off frequency, it will pass above and below a particular range of frequency whose cut-off frequency are pre-determined depending on the value of components used in the circuit design, right, by changing the value of R and C we can change the value of FL and FH, right, or we can pass certain band of frequency, we can reject certain band of frequency, alright.

Now any frequency between these two frequencies are attenuated, it has two pass bands and one stop band as you can see from the figure, so band reject filter, right, it has a RC low pass filter will combined with an RC high pass filter.

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Band Reject Filter

- In Band Pass filter action we have seen that a basic RC low pass filter can be combined with an RC high pass filter to form a simple filter that will pass a band of frequencies either side of two cutoff frequencies
- We can also combine these RC filters to form another type of filters that can block or severely attenuate a given band of frequencies between two cutoff frequencies and pass all other frequencies. This is the Band Reject or the Band Stop filter
- If this "stop band" is very narrow or highly attenuated over a very small range of frequencies, while passing all other frequencies, it is more commonly referred to as the "**Band Notch Filter**". This is because its frequency response shows a deep notch with high selectivity
- A typical Band Reject Filter frequency response is shown in Figure 1 aside

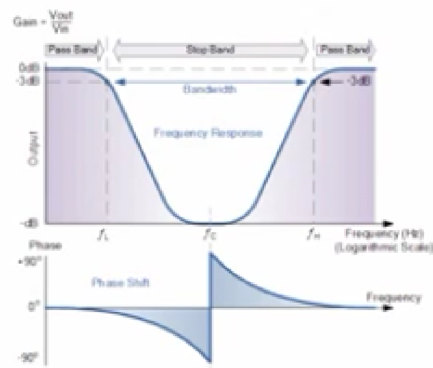

Figure 1

Now we can also combine this RC filters to form another type of filters that can block or severely attenuate a given band of frequencies between two cutoff frequencies and pass all the other frequencies, right, so by tweaking the values of R and C we can just allow a certain band of frequency to pass or even a single frequency to just block, right, so only single frequency to attenuate or band of frequency to attenuate, so if it is just a small frequency or very low range of frequency or very small range of frequency while it can pass all the other frequency, then it is called notch filter, right, so if this stop band is very narrow you can see this stop band is here, right, and if the stop band is extremely narrow that means only a certain frequencies are stopped, only small range of frequencies are stopped than it will work as a notch filter, right, because the frequencies response when you see this response it will show like a notch, so deep notch with high selectivity. A typical band reject filter frequency response is shown here, you can see here.

Now if I want to design the band reject filter, then this is the circuit that is used for designing, as a low-pass filter, high-pass filter in a parallel configuration and then there is a summing amplifier, right, so how does it works?

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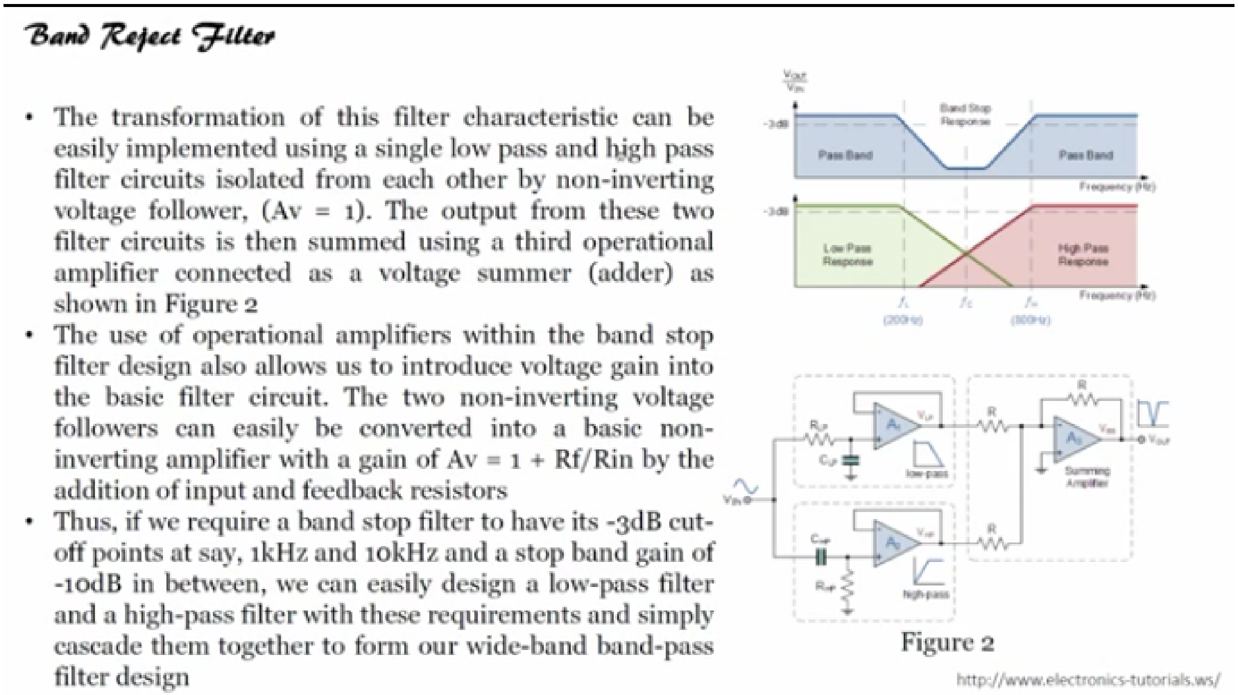

The transformation of this filter characteristic can be easily implemented using a low-pass and high pass filter isolated from each other by non-inverting voltage follower, right, see voltage follower is here, it is here, right, the use of Op-Amp within the band stop filter design also allows us to introduce voltage gain into the basic filter.

Then the two non-inverting voltage followers can easily be converted into basic non-inverting amplifier with a gain of AV = 1 + RF/R in, this non-inverting voltage follower here, or unity gain amplifier can be converted to amplifier by changing the RF/R in, right we can connect RF/R in, thus if we require a stop band filter to have its -3DB cut-off, say at 1 kilohertz and 10 kilohertz and a stop band gain of -10 DB in between we can easily design a low-pass and high-pass filter with these basic requirements, right.

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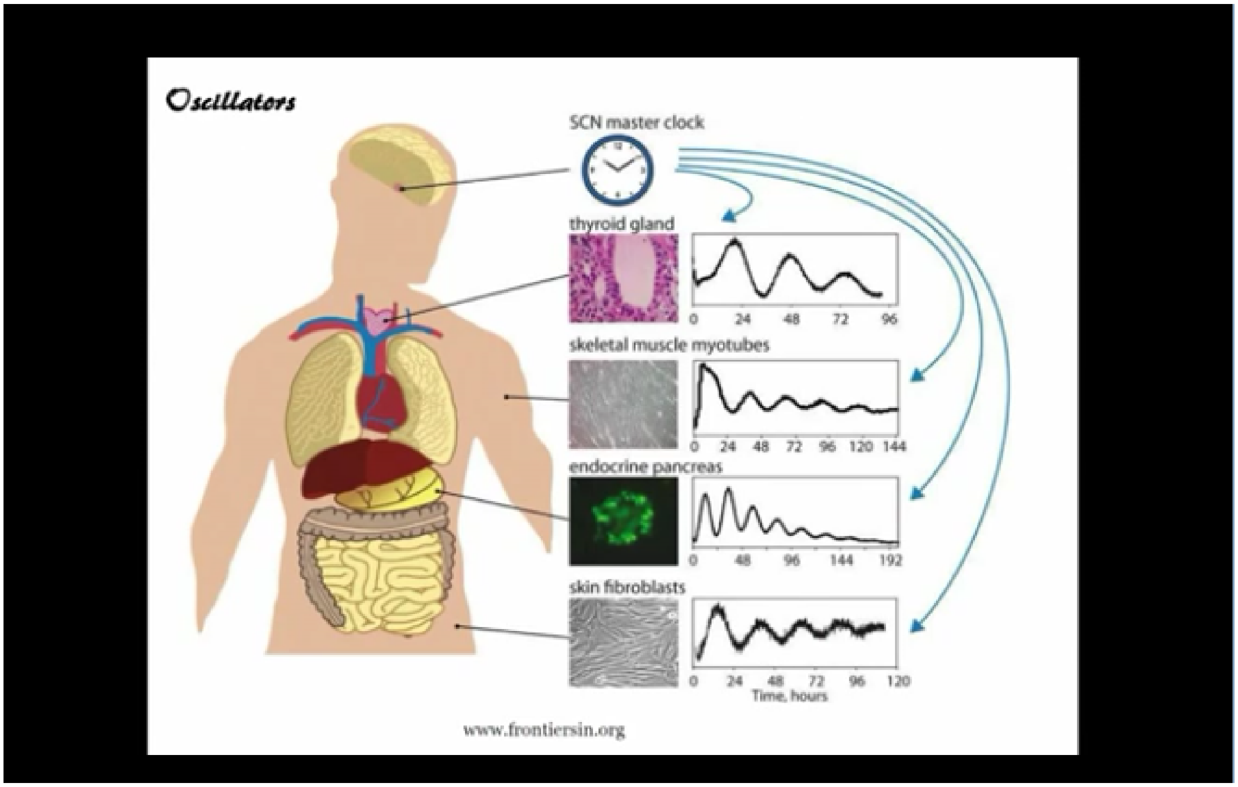

Then we have seen oscillators, so when you talk about oscillators we have seen Barkhausen criteria, and what does Barkhausen criteria says? Barkhausen criteria says that let's see, if one what does it say? One is that the phase,

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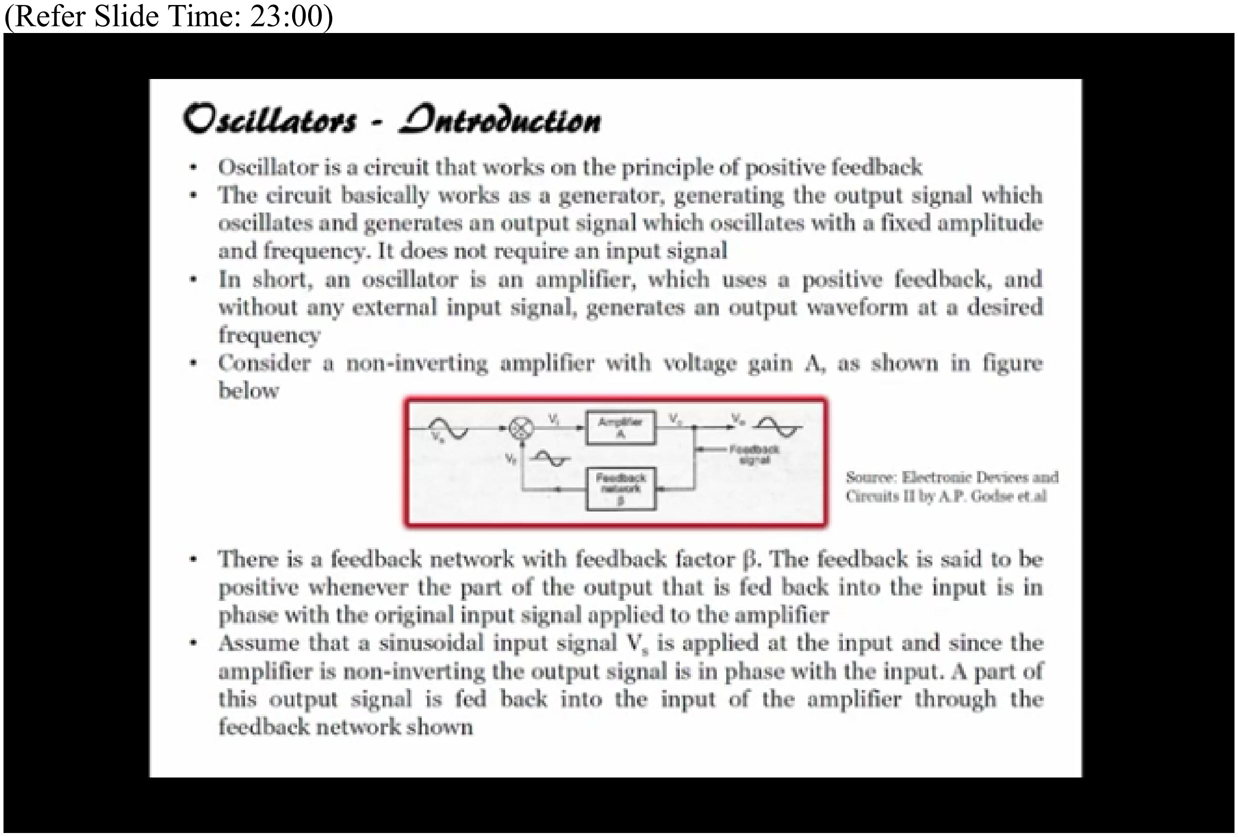

the output signal that is sent back to the input, the feedback signal right should be in phase with respect to input signal, right, so the phase shift, the phase shift right of the output signal compare to input signal or the feedback signal, compare to input signal should be 0 or 360 degree phase.

Second it says that the mode of A into beta should be greater than equal to 1, two criteria's okay, so first is that the oscillators, when you want to design an operational amplifier as an oscillator then you have to apply a positive feedback, right, and as you can see here right that there is a signal VS, there is a input signal VI, this input signal VI depends on VS and the feedback signal VF, there is an amplifier which amplifies the signal and the output, the part of the outputs signal is feedback to the input and what I said is that the part of the output signal that is feedback to the input should have same phase with respect to the input signal, alright.

So let us see,
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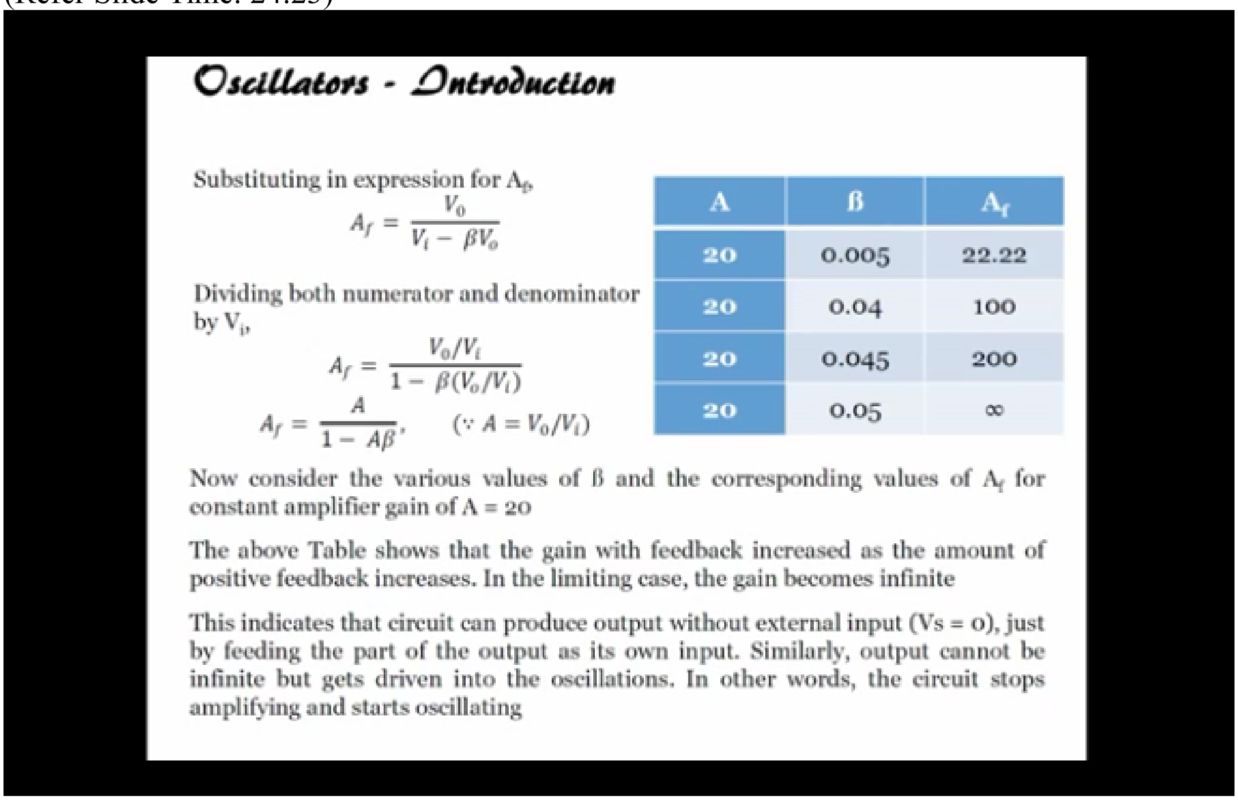

you can see here that only a part of output signal is feedback, if I increase the beta, if I increase the feedback what I have? I have AF extremely high, and in case of 0.05 for a gain of 20 I see that the feedback gain is infinite, right,
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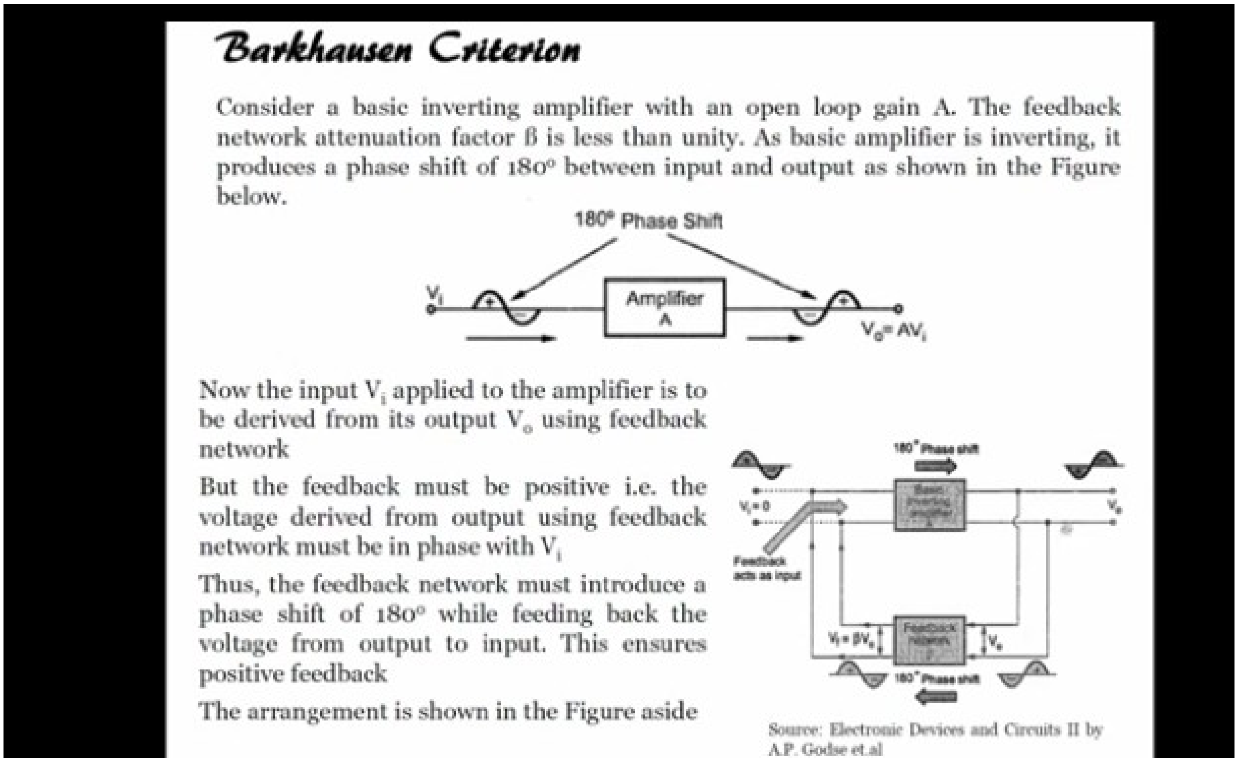

thus we had to follow a Barkhausen criteria and you to understand that only a part of the signal is feedback to the input, we have seen this thing in earlier course, just quickly repeating in it here, so that you understand because we will be using this for actual implementation of circuits, alright.

So you can see that the feedback must be positive, voltage derived from output using feedback network must be in phase with VI, right. Thus if I use an inverting amplifier, as you can see here right you can see the signal here, and signal here it is 180 degree phase shift compared to the input signal, correct, so if I want to feedback, if I want to feed this particular output voltage through the feedback network back to the input, then the feedback networks to introduce another 180 phase shift, right, because you see 0, 180, 180 is fed here if I want to make it 0 or 360, another 180 degree phase shift I will implement in the feedback network, right, so feedback should be having 360 degree phase shift or 0 degree phase shift, right.

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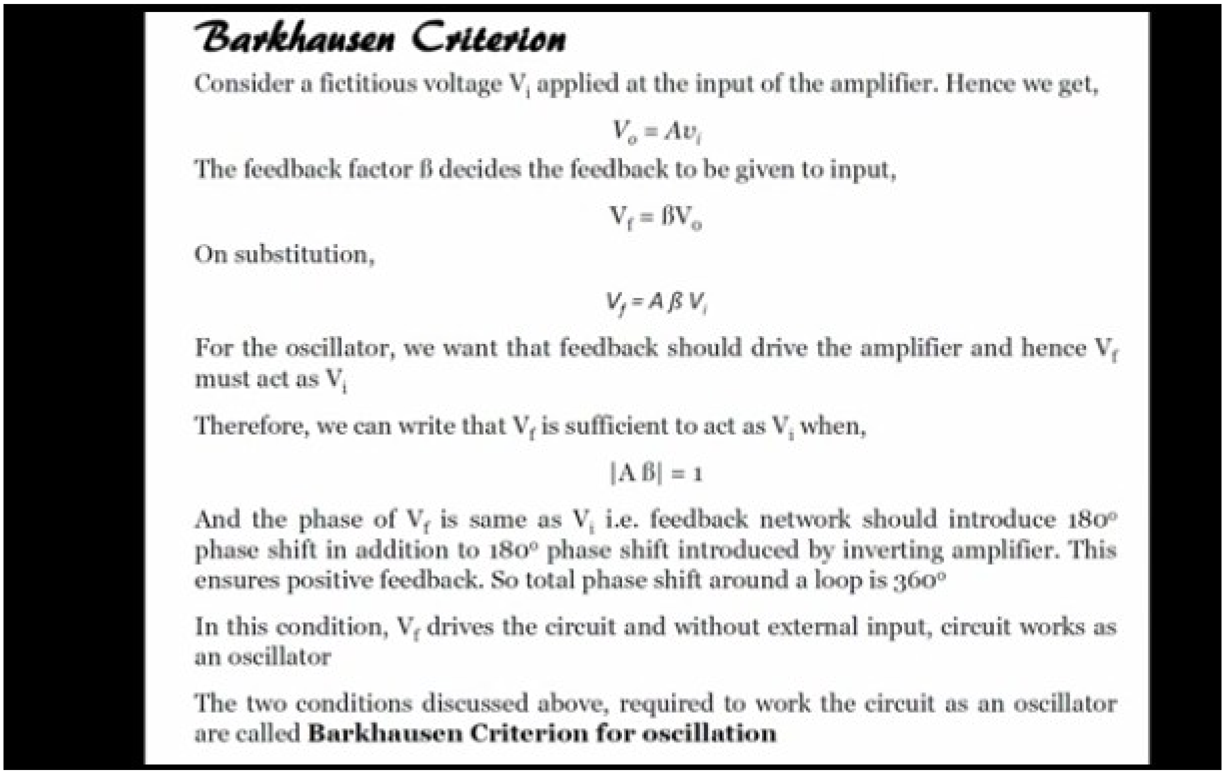

Another point that we discuss is mode of A beta should be equal to 1 or greater than or equal to 1, because initially you want to start the oscillator, then mode of A beta should be greater than 1 and then you can make it equal to 1, alright, so this is very important criteria you were to understand and you had to design a circuit that can follow this criteria, otherwise the oscillations would not happen, alright.

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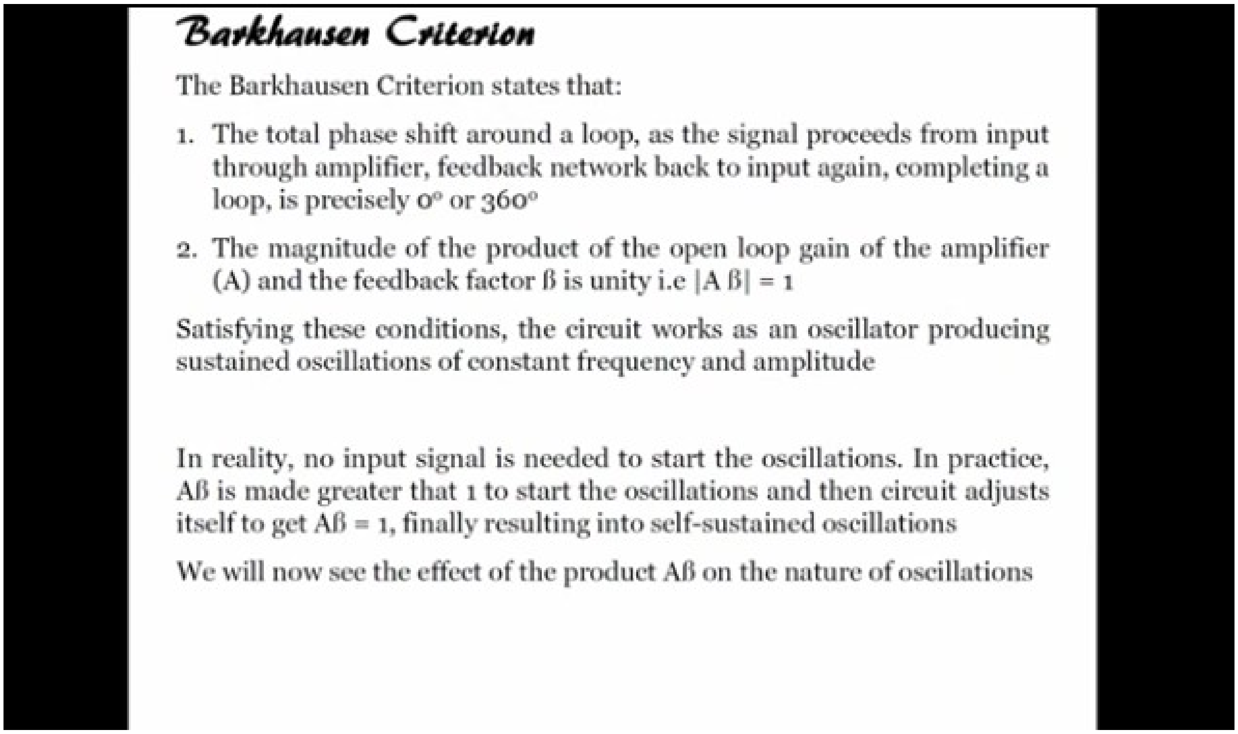

So what are the states? We have already discuss, first is the total phase shift around a loop, as the signal proceeds from input through amplifier, feedback network back to the input completing a loop is precisely 0 or 360, and second is the magnitude of the product of the open loop gain and feedback factor beta should be 1, alright.

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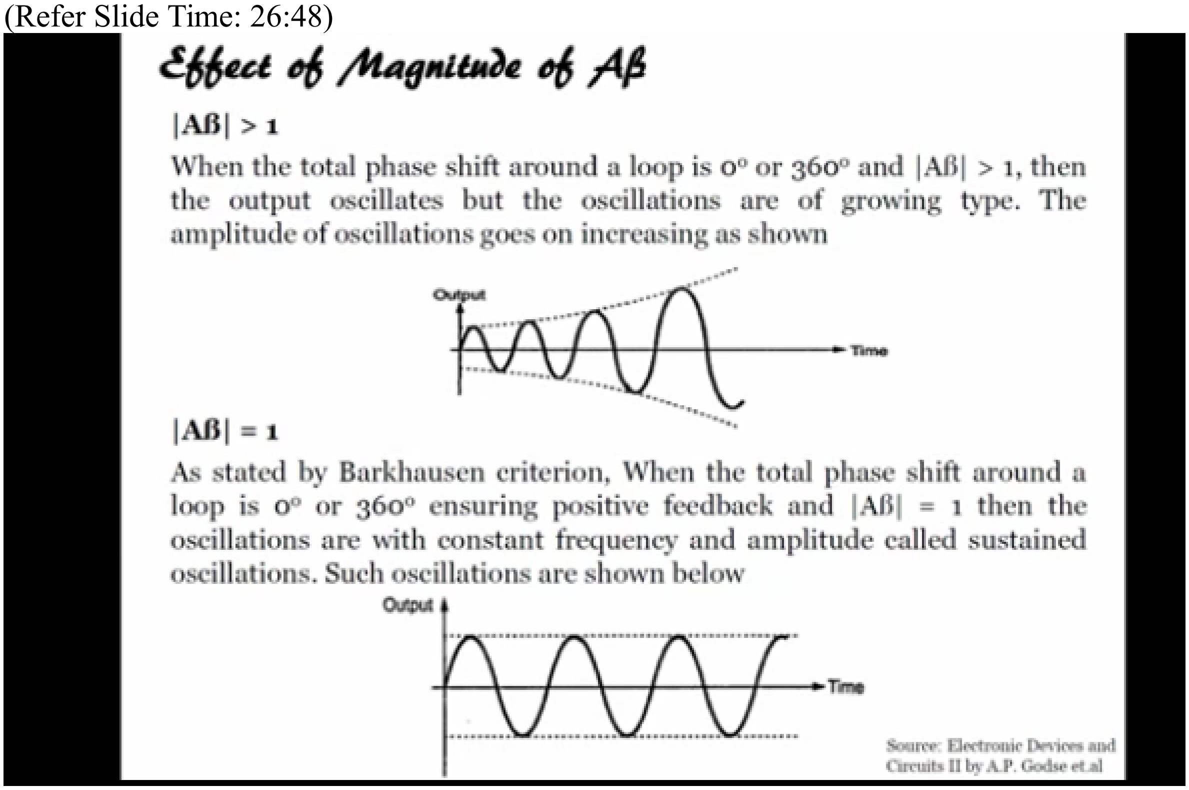

So what happens if it is greater than 1? What happens if it is equal to 1? And what happens if it is less than 1? What A into beta? A is gain, beta is feedback, so when the total phase shift around a loop is 0 degree or 360 degree, and A beta is greater than 1, then the output oscillates or the oscillations are growing type, you can see the oscillations are growing in nature, right, but when you talk about A beta = 1, then you will see that the total phase shift around phase shift is 0 or 360 degree, this is still we have to maintain this condition, but if I have A beta = 1, then the oscillations are with the constant frequency and they are called sustained oscillations, oscillations are sustaining, right.

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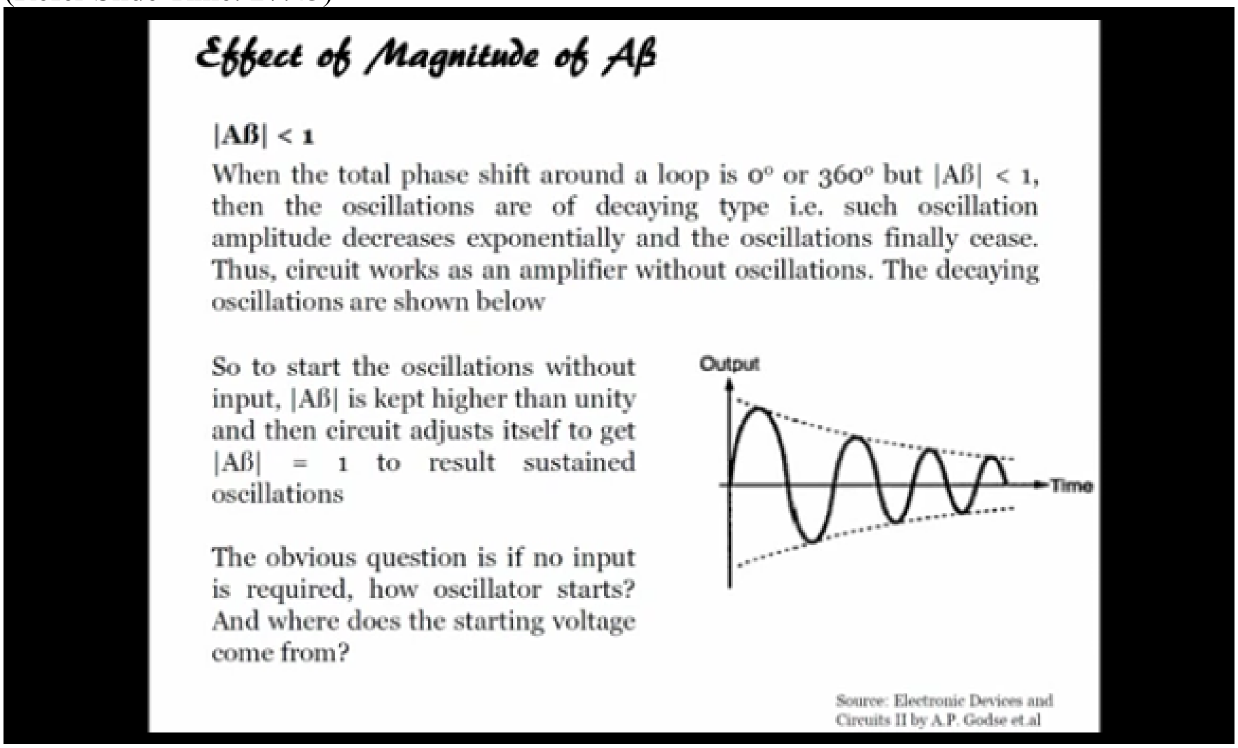

But if I have A beta less than 1, then what will happen? Then the total phase shift around the loop is 0 degree, 360 degree, see every time we have to write the sentence, phase shift should be 0 degree or 360 degree, but if I have A beta less than 1 then I will see a damping type of oscillation, damping type of oscillation, right, or we can say decaying, the oscillations are decaying, alright.

Now the question comes at how oscillators starts, because if A beta, right, is kept higher than unity and then circuit adjust itself to A beta = 1 to result sustain oscillations, it is okay but the obvious question here is that if no input signal is required, here we say that right in oscillator there is no input signal required, if input signal is not required then how the oscillator starts, and from where does the starting voltage come?

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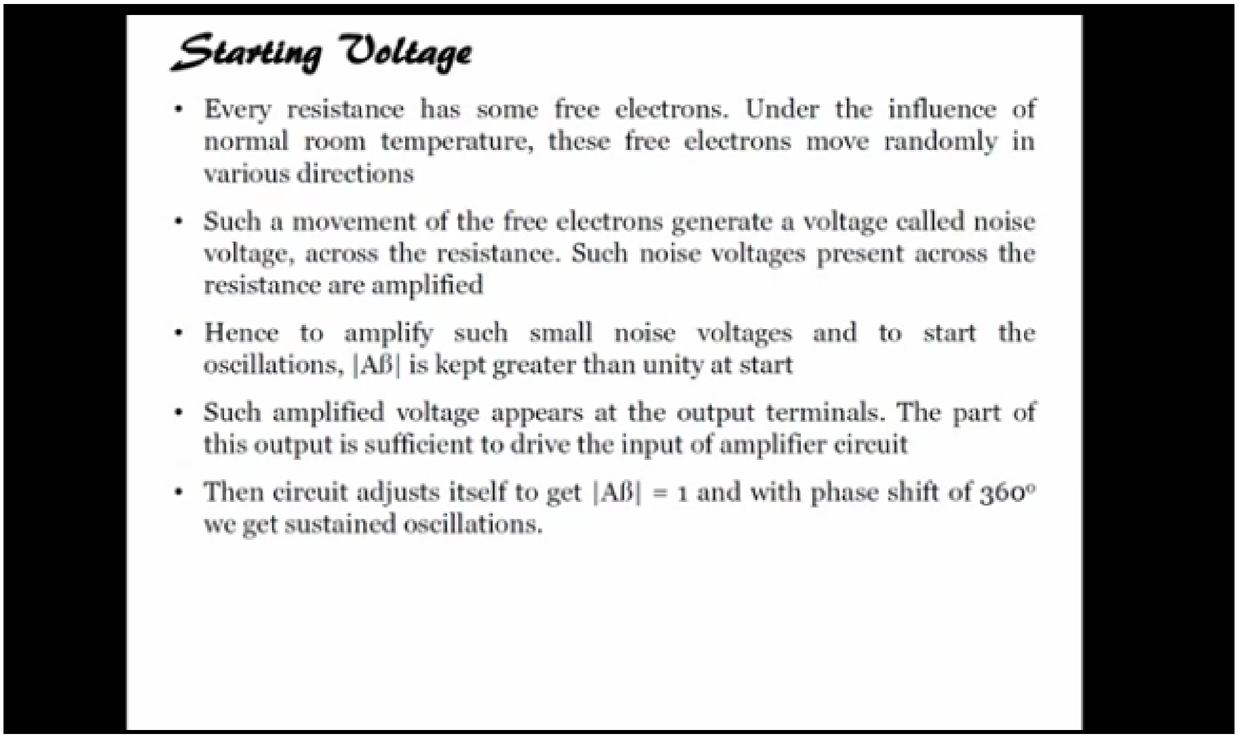

So we can see that the starting voltage comes because of the free electron, because every resistance has a free electron and the influence of a normal room temperature these free electrons move randomly in to various directions, right, such electrons will form a voltage called noise voltage, and these noise voltage are amplified, hence to amplify such a noise, small noise voltage is we need to keep A beta or mode of A beta is slightly greater than 1 or slightly greater than unity, right.

Then once we have this oscillations, we can keep A beta = 1 and phase shift 360 degree to have a sustain oscillations, right, this is a starting of the oscillator.

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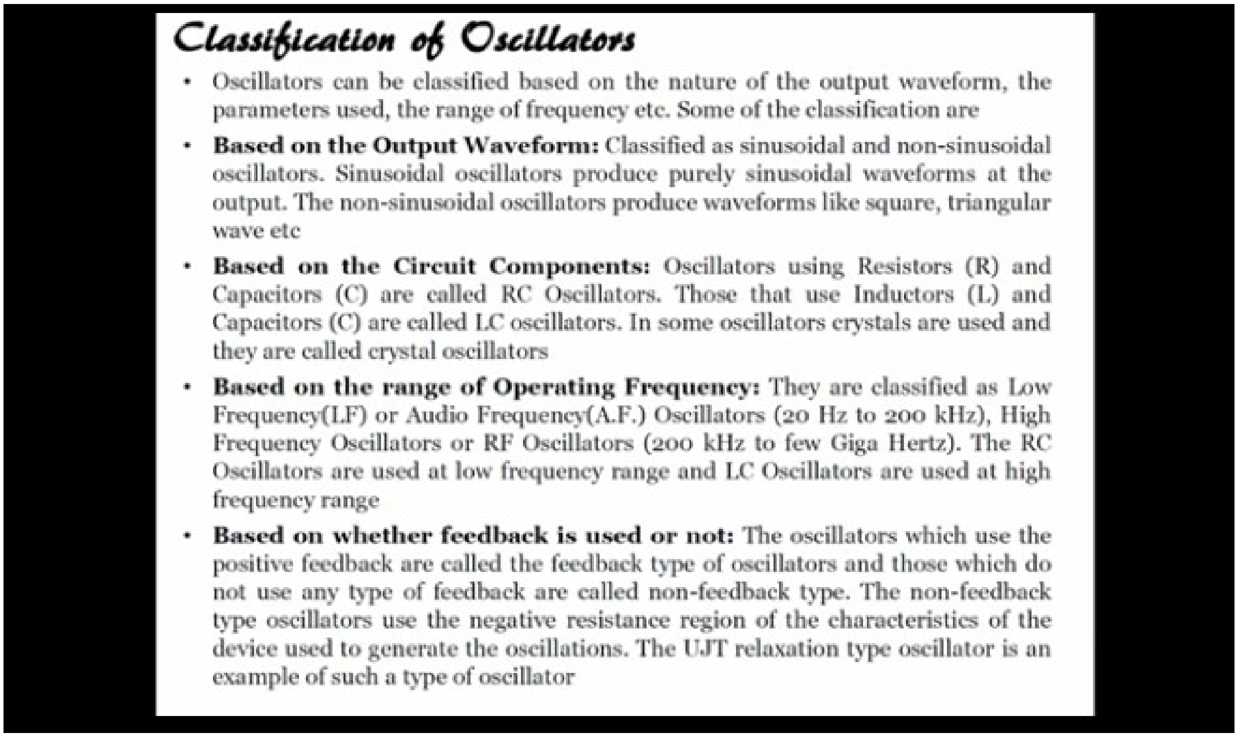

Now if you want to talk about oscillators, oscillators are classified into several categories based on output waveform, based on circuit components, based on range operating frequency, and based on whether feedback is used or not, these are four different components, therefore different classification of the oscillators, right, and we have seen this let us see once again, classified a sinusoidal or non-sinusoidal, sinusoidal oscillators produce is sinusoidal waveform, the non-sinusoidal oscillator produces square wave, triangle wave etcetera.

Same way based on circuit components, whether we are using R, C, L, LC, right, so if it is R and C, these are C oscillator, if L and C it's a different kind of oscillator, you will see different kind of oscillator but depending on how many L, how many C it can be, Hartley oscillator, it can be Colpitts oscillator, right, so we have to understand that depending on the circuit components we can also classify oscillator, depending on waveform we can classify oscillators, sinusoidal waveform or non-sinusoidal waveform, then based on operating frequency, where low operating frequency, audio frequency, or it is higher frequency, right, so if it is RC oscillator it uses low frequency, is LC oscillator it uses higher frequency, right, so based on frequency we can classify the oscillator.

Then we have based on whether feedback is used or not, if feedback is used it is called feedback type of oscillator, feedback is not use non feedback type of oscillators, right, so we have different classification of oscillators, if you see the screen the non-feedback type of oscillators uses the negative resistance region of the characteristics and this is a UJT relaxation type oscillator, so UJT relaxation type of oscillator is your non-feedback type oscillators.

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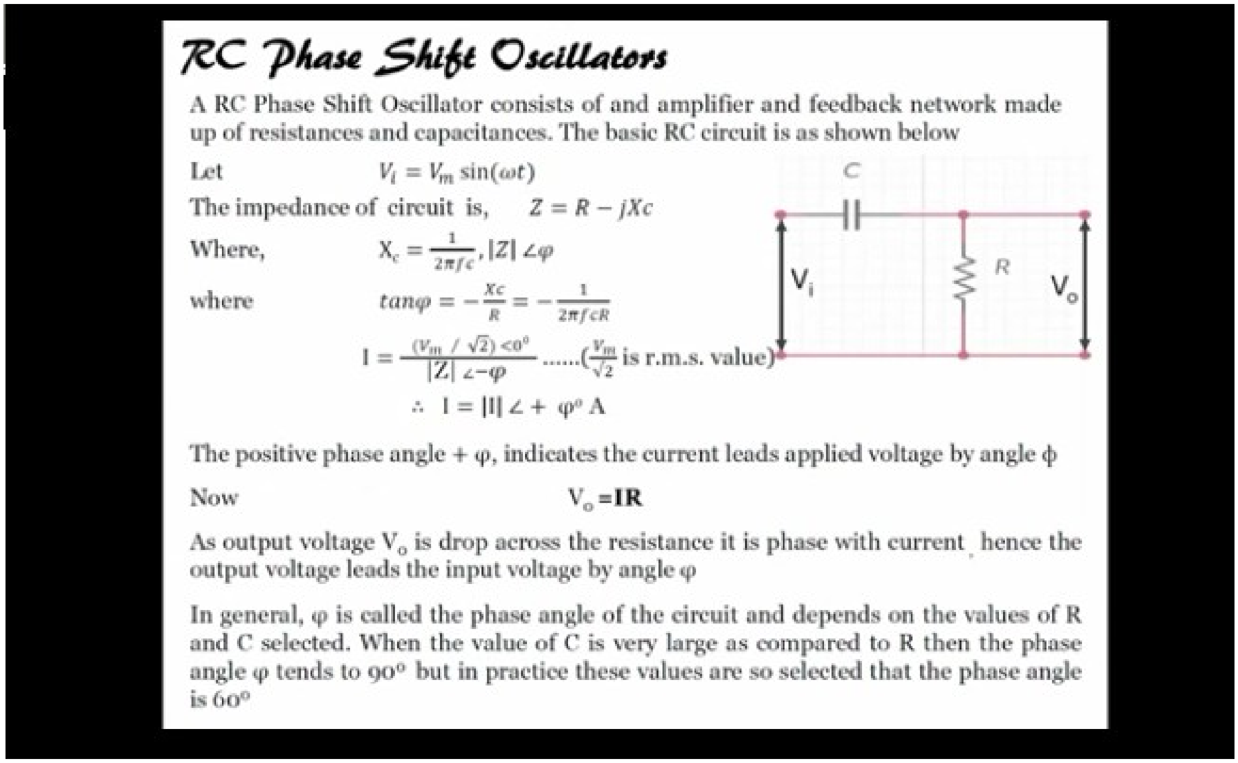

So if we discussed phase shift oscillators or RC phase shift oscillators, then it is in this particular configuration, you can see C and R, now if I work on this circuit, if I want to work on the circuit and I solved this circuit, right, what will I have? Let VI = VM sine omega T, if this is the input, right, an impedance circuit is equals to R-JXC, where X is nothing but 1/2 pi FC into Z and the mode of Z should be less than your theta or phi, so if I solve this then what will I have? I will have I equals to this particular equation, right, mode of I angle + phi degree into A, the positive phase angle indicates the current leads applied voltage, you can see here there is a positive phase angle right, and this positive phase angle what does it says? It says that the current leads applied voltage by angle phi, and now VO = IR.

So it’s the output voltage VO is drop across the resistance and it is in phase with the current, hence the output voltage leads the input voltage by angle phi, correct, output voltage leads by angle phi. In general phi is called phase angle of the circuit, and depends on the value of R and C, when the value of C is very large as compared to R then the phase tends to be 60 degree, so for a single C and R the value of C is higher, than we can add a phase shift of 90 degree, but in practice this values are so selected that phase shift is 60 degree, right, so if your C is high, right compared to R then we have a phase angle of or phase shift of 90 degree, but we have to adjust R and C such that we have a phase shift of 60 degree, why? Because these RC circuits are used in the feedback,
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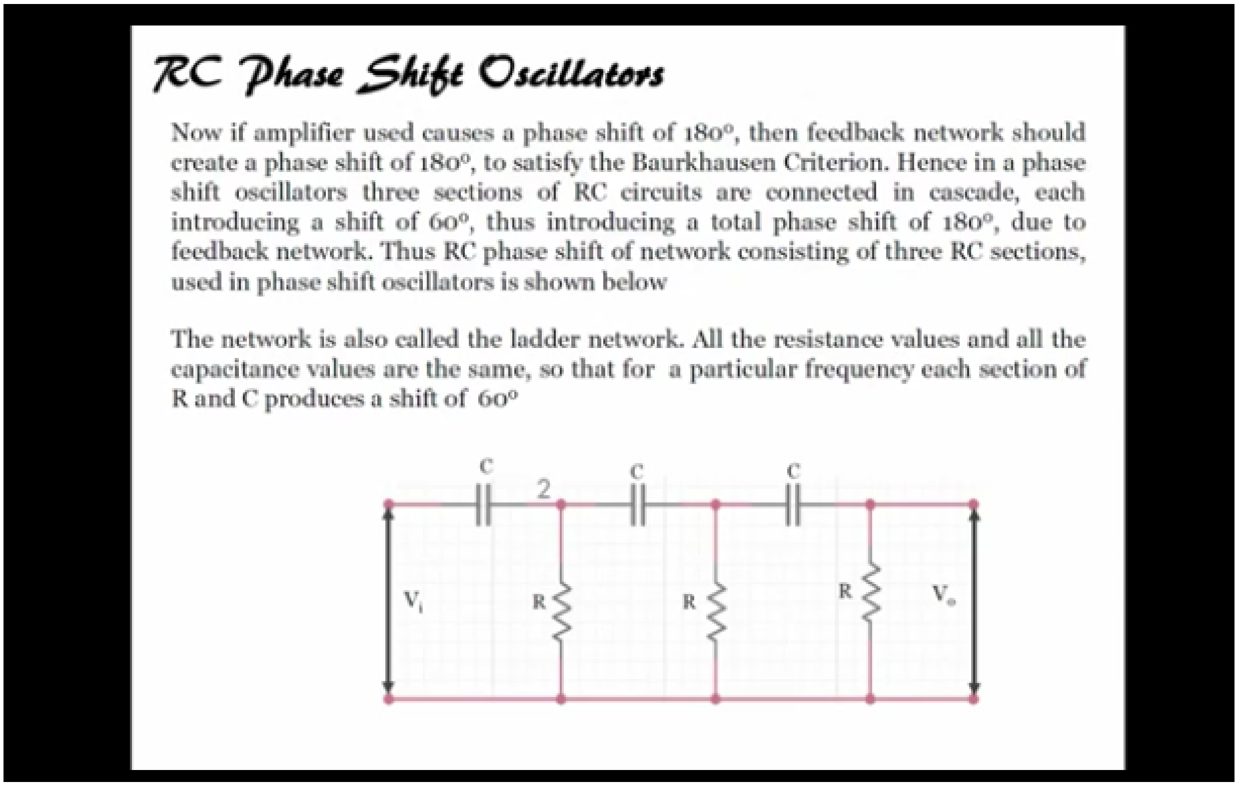

so if I have a feedback that means that each RC producing 60 degree, three RC will produce 180 degree, right.

So if I have a phase shift of 180 degree at the output compared to the input signal, then if I feed this output back to this RC circuit I'll have another 180 degree phase shift, so my total phase shift is 360 degree or 0 degree which will satisfy my Barkhausen criteria, right, that's a use of RC.

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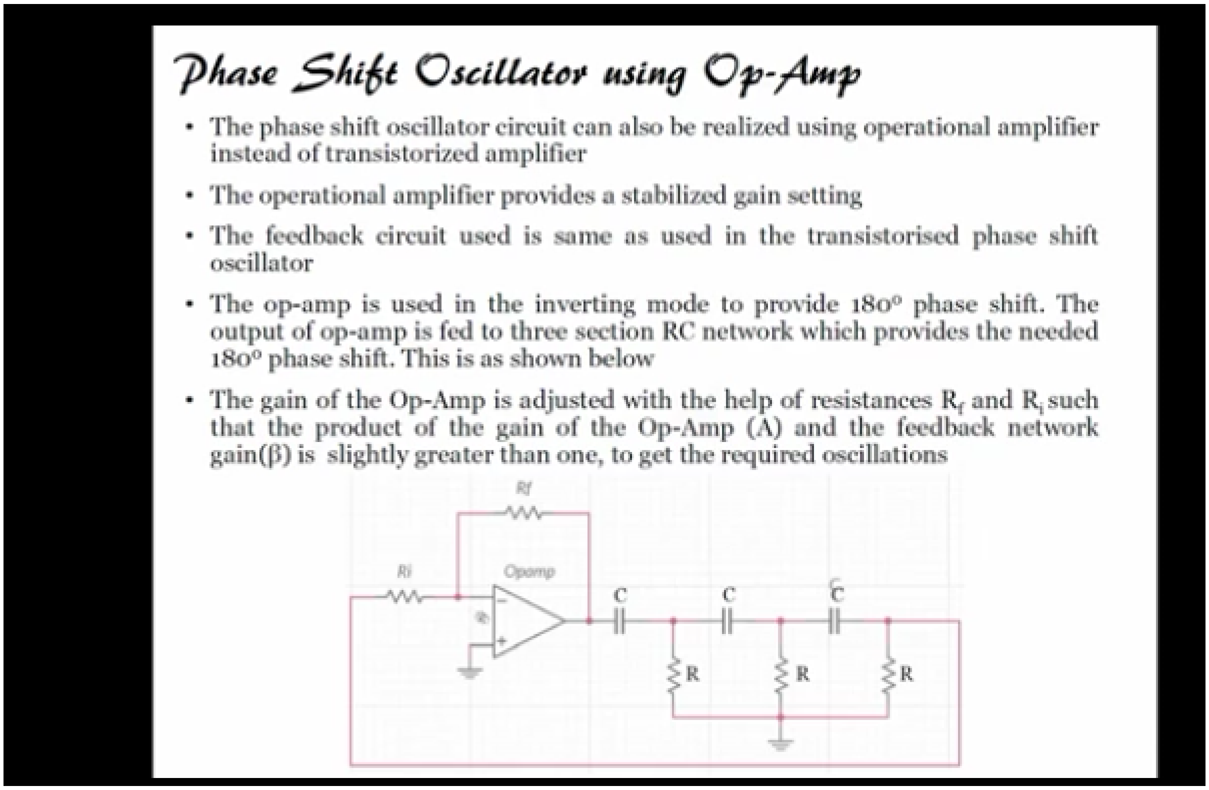

So you can see here if the signal is applied to the inverting terminal right I have a 180 degree phase shift at the output, I'm feeding it to the RC feedback circuit, and I'll have another 180 degree, so 180 + 180 will be 360 degree, and some part of the signal is fed back to the input to sustain the oscillations, right, we have seen this,

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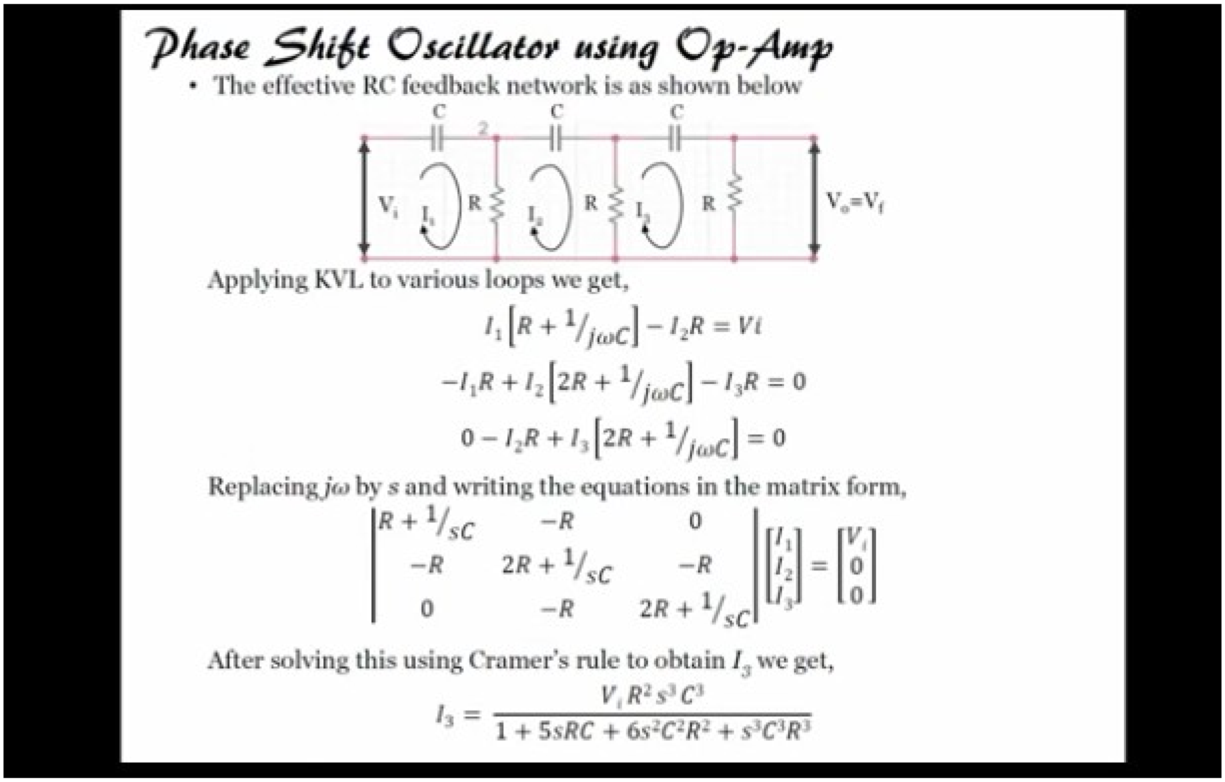

we have also derived the equation for the gain and equation for the beta, right, and what we found is that beta in case of RC phase shift oscillator should be 1/29 while gain should be greater than 29, right.

So you please see my earlier lectures right in another course, the course name is Integrated Circuits, Mosfets, op-amps and their Applications, if you see YouTube videos you will find how we are deriving these equations, equation such as gain, equation such as feedback network or feedback component beta.

So far RC phase shift oscillator we have beta = 1/29, why? Gain = 29, so if you come back to the screen, what we'll see?
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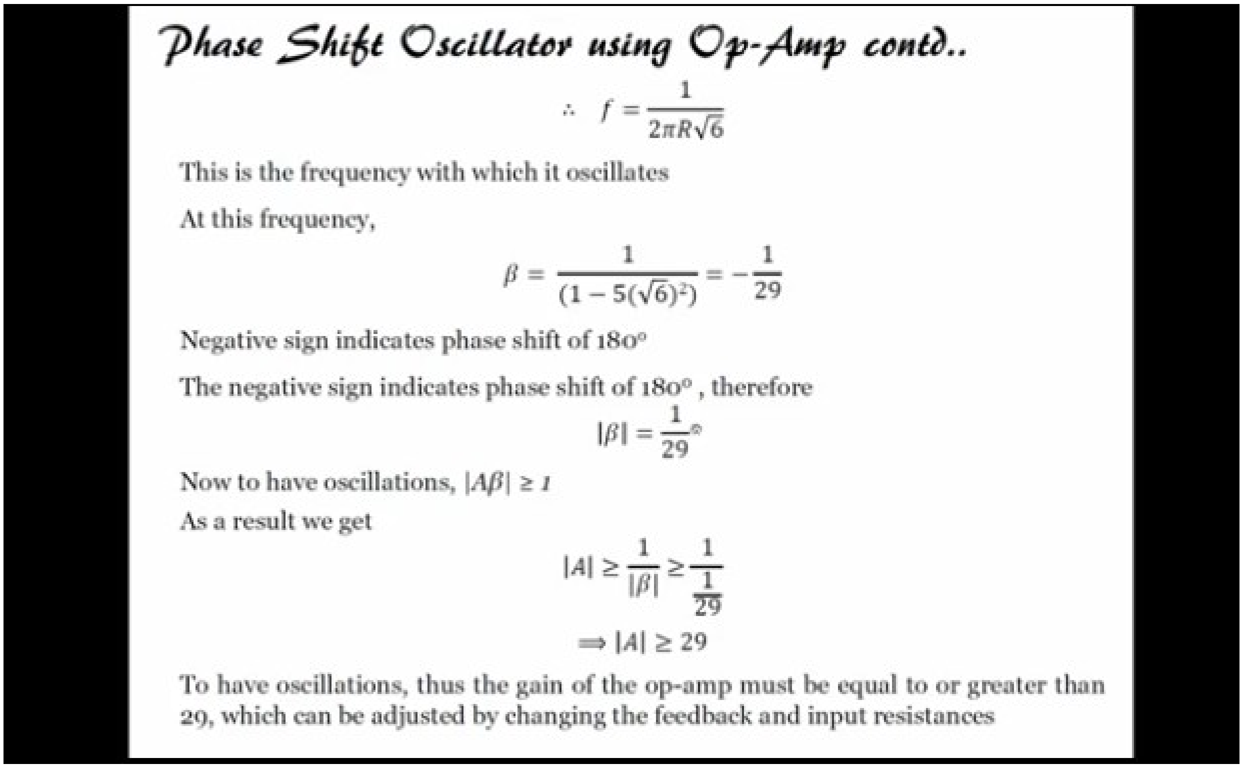

If we have beta = 1/29 and gain is greater than or equal to 1/29 then mode of A into beta would be greater than equal to 1, and I have a phase shift of 0 degree or 360 degree, thus I'm satisfying the Barkhausen criteria, thus to have the oscillations, the gain of Op-Amp must be equal to greater than 29 which can be adjusted by changing the feedback and input resistance.

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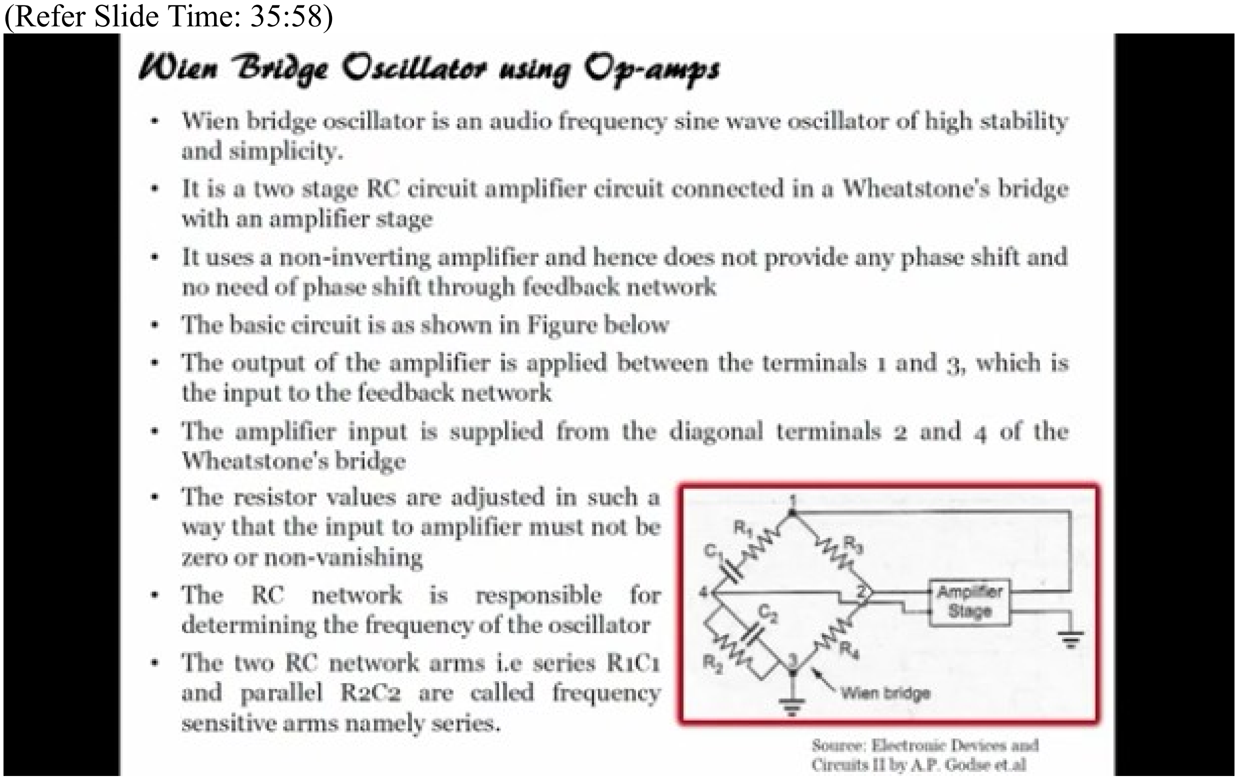

Now let us see another oscillator which is Wien Bridge oscillator, alright, and in Wien Bridge oscillator there is no phase shift, phase shift is not there, so Wien Bridge oscillator is an audio frequency sine wave oscillator of a high stability and simplicity, it has 2 RC amplifier circuit connected in Wheatstone, you can see here, RC here, RC here, right one is in series, and then is parallel right, the basic circuit is shown in figure, output amplifier is amplified between terminal 1 and 3, 1 and 3, right, the output amplifier is feedback between terminal 1 and terminal 3, right.

Amplifier input is applied between terminal 2 and 4, right, the resistor value adjusted such that the input to the amplifier must not be zero or non-vanishing, right, the RC network is responsible for determining the frequency of oscillator, RC network which is here and here, it determines the frequency of the oscillator.

So here how many RC oscillators? Here there are 2 RC oscillators, right, one series R1 C1, another parallel R2 C2, right, and these are called frequency sensitive arms. So if you consider just feedback then R1 C1, R2 C2,
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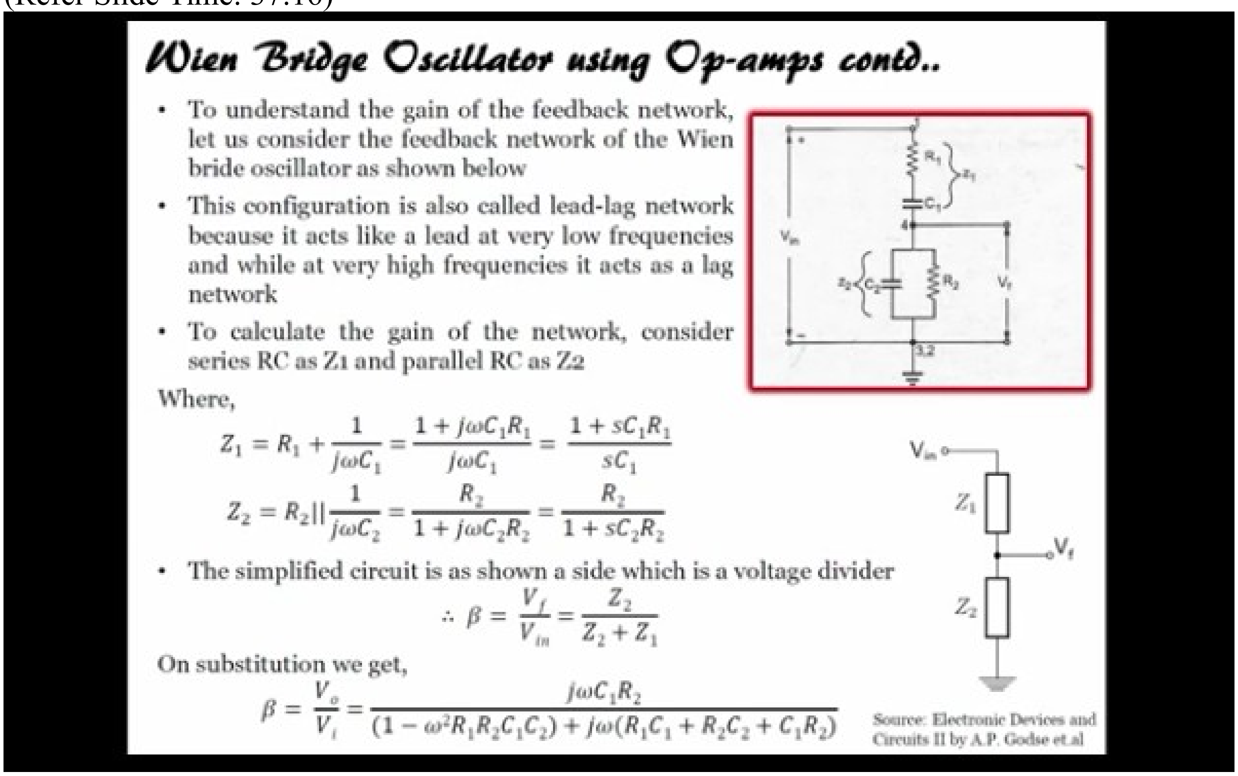

in this particular configuration I'll say R1 C1 is Z1, R2 C2 is Z2, right, I'm applying input between 1 and 3, so V in, output is between 2 and 4, sorry 2 and 1 and, let's see what is that? 1 and 3 is the output feedback from the amplifier, and between 2 and 4, between 2 and 4 my feedback is there, right.

So solving this particular equation solving this, what we will get?
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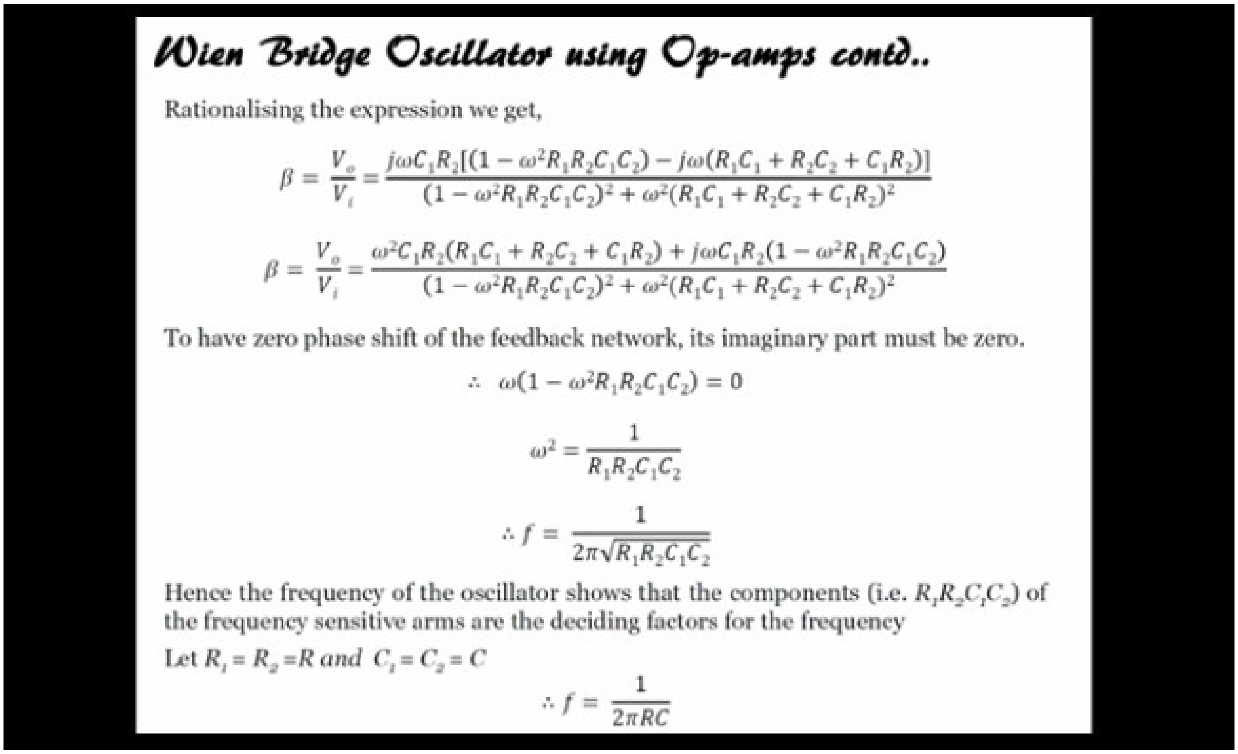

We get F = 1/2 pi RC, the frequency formula for this oscillator is 1/2 pi under root of R1 R2 C1 C2, but when R1 = R2, and C1 = C2 we have 1/2 pi under root of R square C square, is nothing but 1/2 pi RC, right,

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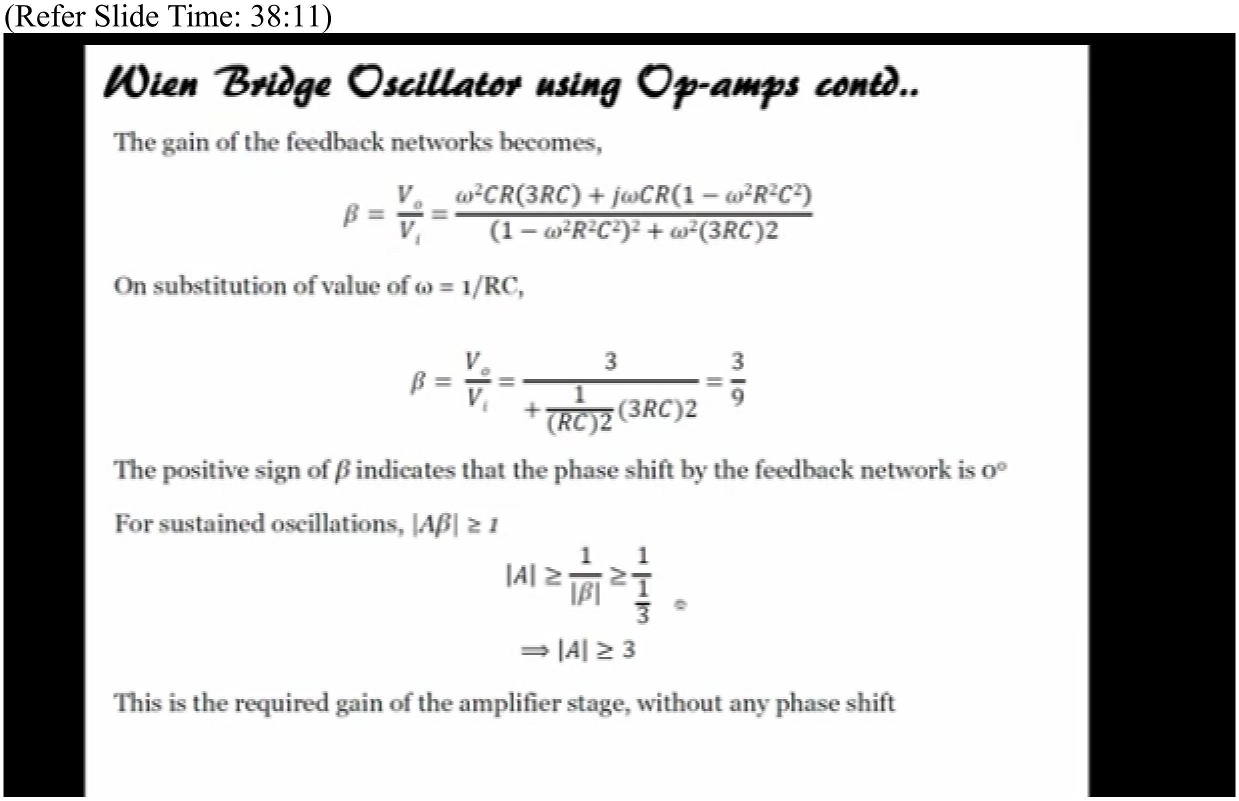

so my beta which is the feedback network here in this case if I solve further, what is that? Beta is nothing but 1/3, right, and what is my gain? My gain should be greater than equal to 3, then only my A into beta would be greater than equal to 1, because 1/3 into 3 is greater than or equal to 1, right, so this is required gain of the amplifier without any phase shift, because there is no phase shift in case of Wien Bridge oscillator, alright, in case of Wien Bridge oscillator there is no phase shift.

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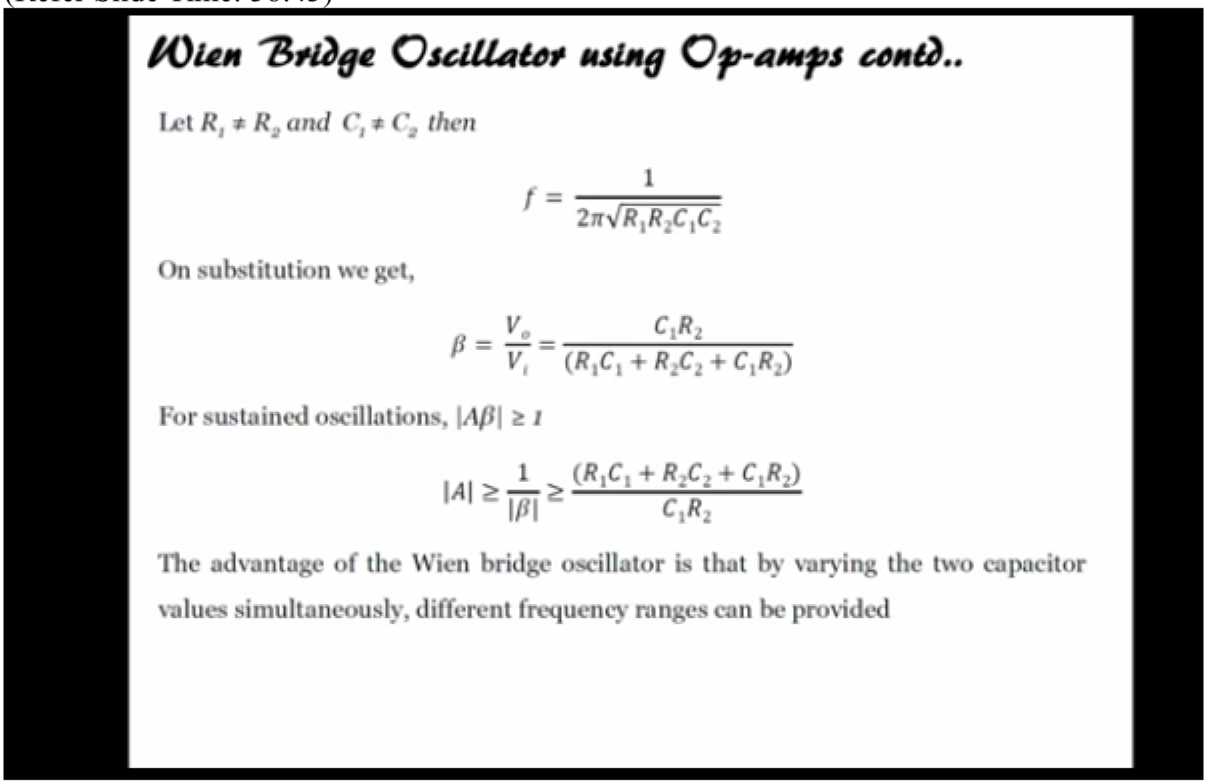

But what if R1 is not equal to R2, and C1 is not equal to C2, then we cannot have a, if F = 1/2 pi RC right, in this case we'll have if on substitution we'll have C1 R2, VO/VI, right beta is VO/VI, so I have this formula and then my A gain would be based on this particular equation, alright, but the advantage of Wien Bridge oscillator right is that by varying the capacitor, varying the capacitor simultaneously right by varying the two capacitor value simultaneously we can have different frequency ranges, this is the advantage of Wien Bridge oscillator.

Second is there is no phase shift require in the feedback network, right, that is the second advantage of the Wien Bridge oscillator, right, so if the amplifier you see,

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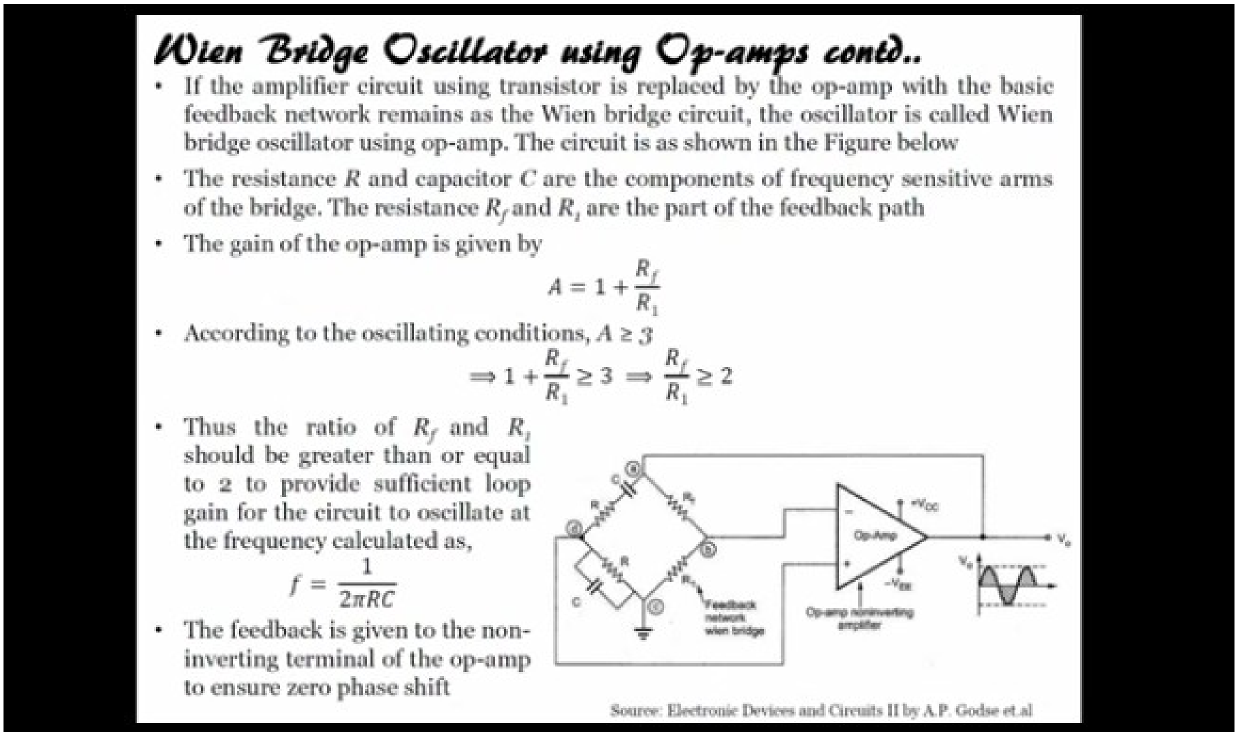

if the Wien Bridge oscillator is used with an operation amplifier right in this particular configuration, right, then what will happen? The resistance and capacitors are the component of frequency sensitive arms you can see here, the resistance RF and R1 are the part of feedback network, right, RF and R1 would be part of the feedback network for the amplifier, and gain would be because signal is provided at the non-inverting terminal there would be 1+RF/R1, right, according to oscillations for Wien Bridge oscillator A should be greater or equal to 3, that mean 1+RF/R1 equal to greater than or equal to 3, or RF/R1 should be greater than or equal to 2, so we can adjust the value of RF/R1 such that my value comes greater than or equal to 2, right.

So for the oscillation to cut the frequency calculated is F = 1/2 pi RC, feedback is given to the non-inverting terminal of the op-amp to ensure the zero phase shift, right, feedback is given to the non-inverting terminal you can see here so that we have a zero phase shift at the output, right, so this is about this particular module and we have seen how the oscillators can be designed as well as we have also seen how the filters can be designed, right.

In the next module which is a last module for the summary so that we understand how we can implement these things in the practical applications, right, we'll be looking at few other oscillators that are LC oscillators, and we will see that how we can change the inductors and capacitors, the value of inductor and value of capacitor to obtain the LC oscillators. LC oscillators as we have discussed are used for higher frequency applications, and RC oscillators are used for low frequency applications, right. So let us see in the next class how we can design LC oscillators and that will be the last module for this particular lecture, alright, so I'll see you in next class, just go through this and refresh your understanding about op-amps and its application, then we have to actually implement those op-amps for refund applications, alright. I'll see you in next class till then you take care. Bye.