Integrated Circuits and Applications

Prof. Shaik Rafi Ahamed
Department of Electronics and Electrical Engineering Indian Institute of Technology, Guwahati

Characteristics of Practical Operational Amplifier
Lecture – 09
AC Characteristics (Frequency Response)

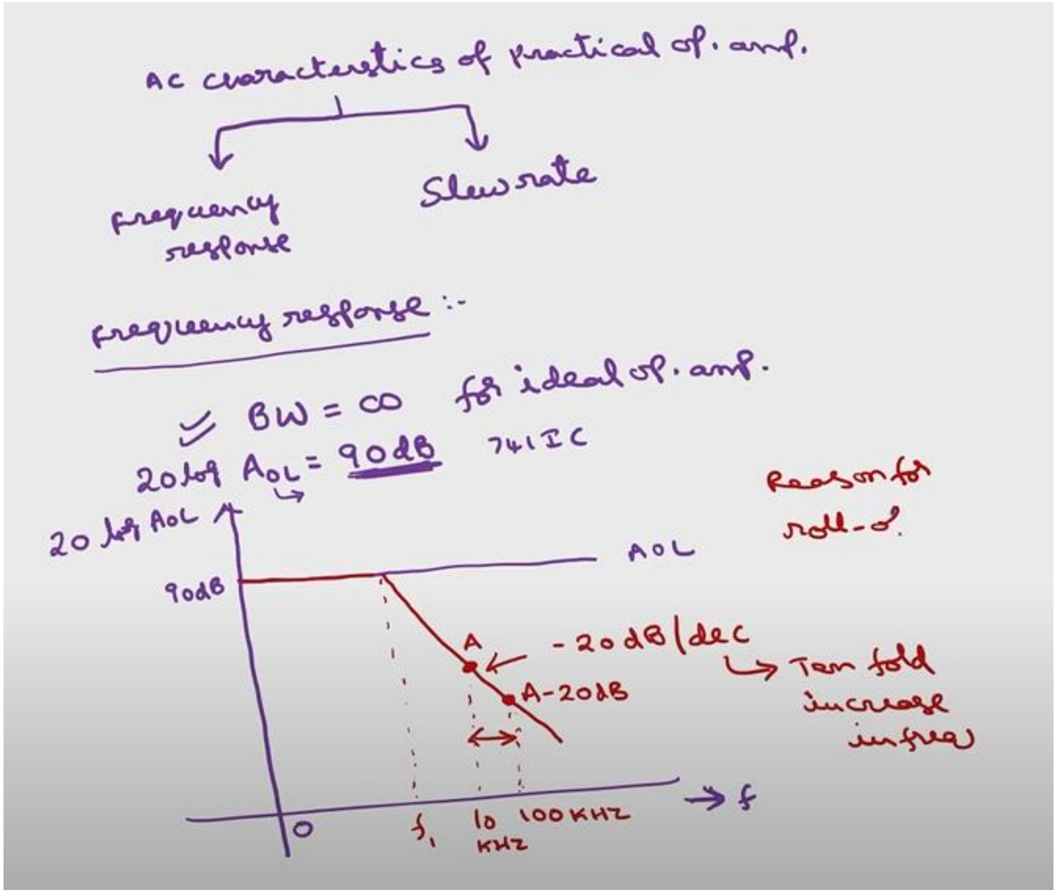
Ok. In the last lecture we have discussed about some of the DC characteristics of a practical op amp which are going to affect the performance of the operational amplifier. So, today we will discuss about some AC characteristics of practical amplifier which affects the performance of operational amplifier. So, basically two AC characteristics which are going to affect the operational amplifier performance, one is called frequency response, another is called flow rate. First, I will discuss about the frequency response, how this frequency response is going to affect the performance of the operational amplifier. If it is ideal operational amplifier bandwidth is infinity for ideal op amp. And open loop gain is say A_{OL} which is of the order of 90dB in case of operational amplifier 741 IC.

So, the meaning of this bandwidth infinite is so, if you plot this 90dB in fact, this is 20 logarithm of A_{OL}. So, normally this magnitude will be plotted on the logarithmic scale this is dB, dB means decibel. So, which is normally used to represent a wide range of values ok, here if this gain varies over a wide range. So, we can represent this by using dB.

So, if this is 90dB in case of ideal operational amplifier for all the frequencies the gain should be A_{OL} as the frequencies varies from DC 0 to infinite frequency. So, it has to provide the constant gain of 20 logarithm of A_{OL} which is of the order of 90dB in case of 741 operational amplifier. But for practical operational amplifier after a certain frequency the gain is going to be roll off. So, if I take the practical op amp so, this is for practical op amp after a certain frequency say f_1. So, the gain will roll off at a rate of $-20dB/dec$, decade means a tenfold increase in the frequency.

That is if I take two points this is say some 10kHz this is 100kHz then this is one decade. And if you take the dB here and here this value is say A then this will be $A - 20dB/dec$. So, for every one decade the gain will decrease by 20dB ok. What is the reason for this roll off? So, the reason for this roll off is there will be a presence of capacitance in the equivalent circuit ok. This capacitance will be caused by the physical characteristics of the device such as BJT or FET.

(Refer to the slide at 04:44)



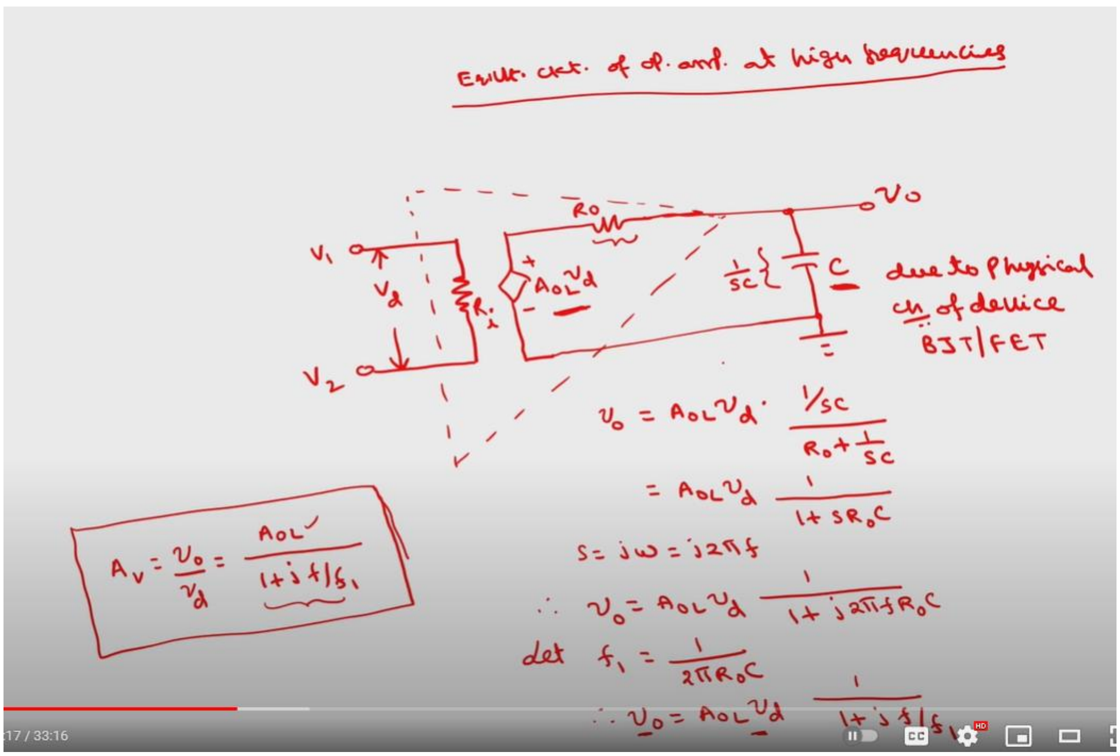
So, if I take the equivalent circuit of op amp at high frequencies there will be capacitance. This is the equivalent circuit this should be grounded. In normal cases, but in case of practical op amp there will be capacitance at the output. This is the difference voltage v_d, this is input resistance R_i, this is output resistance R_O, there will be open circuit. A_{OL} is the open loop voltage gain into v_d.

So, in case of practical op amp there will be some capacitance component which is going to degrade the performance of operational amplifier at high frequencies which causes the gain to roll off by 20dB per decade. So, this capacitance is due to physical characteristics of the device physical characteristics of device such as BJT or FET. So, this operational amplifier will be constructed by using either BJT or FET. Now, what will be this frequency response? In order to study the frequency response of this practical op amp which contains the capacitance at the output. So, we will derive the expression for the voltage gain with capacitance.

So, I will define this voltage gain as A' including this $A = A_{OL}v_d$, is this voltage. There will be voltage divider between this resistance and this capacitance. So, we have discussed how to perform the analysis of the capacitance in the S domain this capacitance will be represented by $\frac{1}{SC}$. So, if this voltage is A_{OL} v_d then the voltage across this capacitor which is v_o. So, this is $v_o = A_{OL}v_d \frac{\frac{1}{SC}}{R_o+\frac{1}{SC}}$.

This is equal to $A_{OL}v_d \frac{1}{1+SR_oC}$, but $S = j\omega = j2\pi f$. Therefore, what is $v_o = A_{OL}v_d \frac{1}{1+j2\pi f R_o C}$. Let $f_1 = \frac{1}{2\pi R_o C}$, then what happens to this $v_o = A_{OL}v_d \frac{1}{1+j\frac{f}{f_1}}$. So, therefore, what is voltage gain? This $\frac{v_o}{v_d}$, is the voltage gain. So, the voltage gain $A_v = A_{OL}\frac{1}{1+j\frac{f}{f_1}}$.

(Refer to the slide at 10:14)



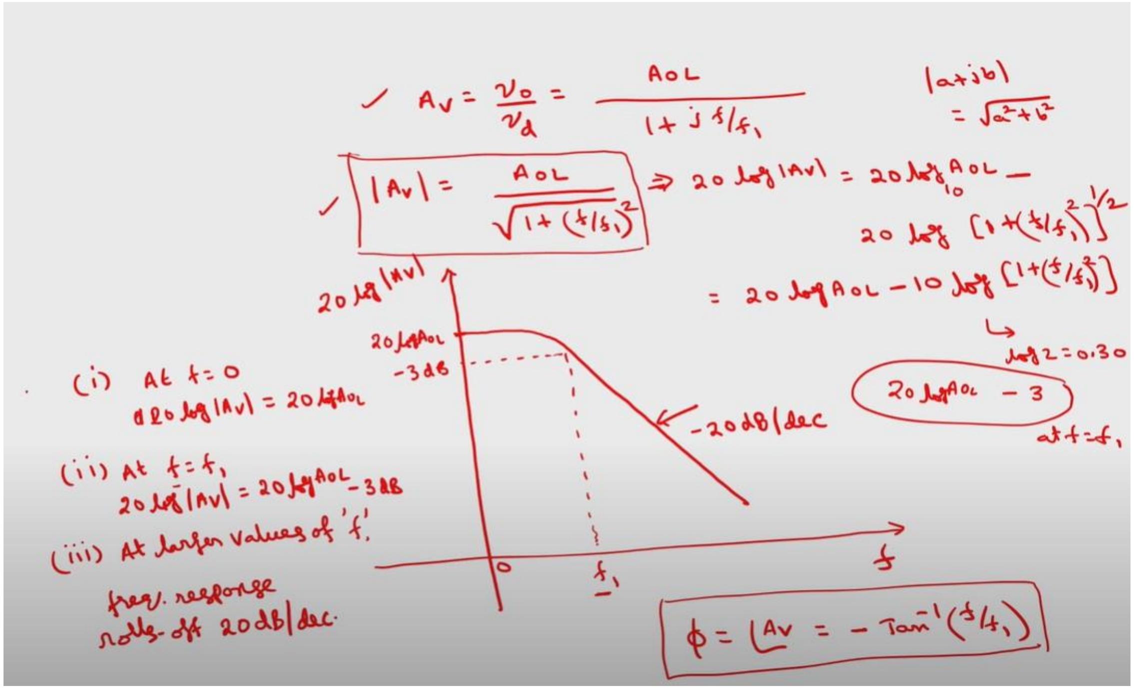
This is the voltage gain of operational amplifier including the capacitance. So, without this capacitance simply A_{OL} is the voltage gain, but with capacitance there will be a factor in the denominator. Now, we will see the frequency response of this operation amplifier with capacitance. So, this voltage gain you have got as $\frac{v_o}{v_d} = A_{OL}\frac{1}{1+j\frac{f}{f_1}}$. So, we can have two responses one is magnitude response another is phase response.

If you want magnitude response of $A_v = \frac{A_{OL}}{\sqrt{1+(\frac{f}{f_1})^2}}$. As $|a + jb| = \sqrt{a^2 + b^2}$. So, if you want to plot this modulus of A_v with respect to the frequency f. We will take 20 logarithm of this A_v as I have told to represent a wide range of values we will use logarithm is scale rather than the normal scale. So, this implies $20\log|A_v| = 20logA_{OL} - 20log[1 + \left(\frac{f}{f_1}\right)^2]^{\frac{1}{2}}$. This is $log\frac{A}{B} = logA - logB$.

So, this half we can take to the in front of this one. So, this will be $20\log|A_v| = 20logA_{OL} - 10\log\left[1 + \left(\frac{f}{f_1}\right)^2\right]$ow, we will see what are the characteristics of this 20 logarithm of modulus of A_v. At $f = 0$, here if you substitute $f = 0$, this becomes 1 plus 0. So, log 1 which is $log1 = 0$.

So, simply $20\log|A_v| = 20logA_{OL}$. So, here $20logA_{OL}$. Second one at $f = f_1$. So, this becomes 1. So, 1 plus 1 to log 2, $log2 = 0.3010$, this becomes log 2 at $f = f_1$. So, whose value is 0.3010 approximately 0.3 say. So, 0.3 into 10 becomes. So, this is minus 3. So, this is $20logA_{OL}$-3, this will be the value at $f = f_1$, means whatever the value at $f = 0$ at $f = f_1$, there will be 3dB decrease. So, this will be having high frequencies. So, at $f = f_1$, there will be some 3dB decrement in the gain. So, this is $20logA_{OL} - 3dB$, and after that this $20\log|A_v| = 20logA_{OL} - 3dB$. Third one for larger value of f there will be a roll off of frequency response rolls off at a rate of 20dB per decade. So, here at the high frequencies above this f_1 there will be a $-20dB/dec$ decrease in the gain. So, you see about the magnitude or the amplitude characteristics ok. So, what about the phase characteristics? So, this is A_v magnitude is this what about the phase angle if I call ϕ as angle of A_v this is nothing, but numerator angle is 0 and denominator angle is $-tan^{-1}(\frac{f}{f_1})$.

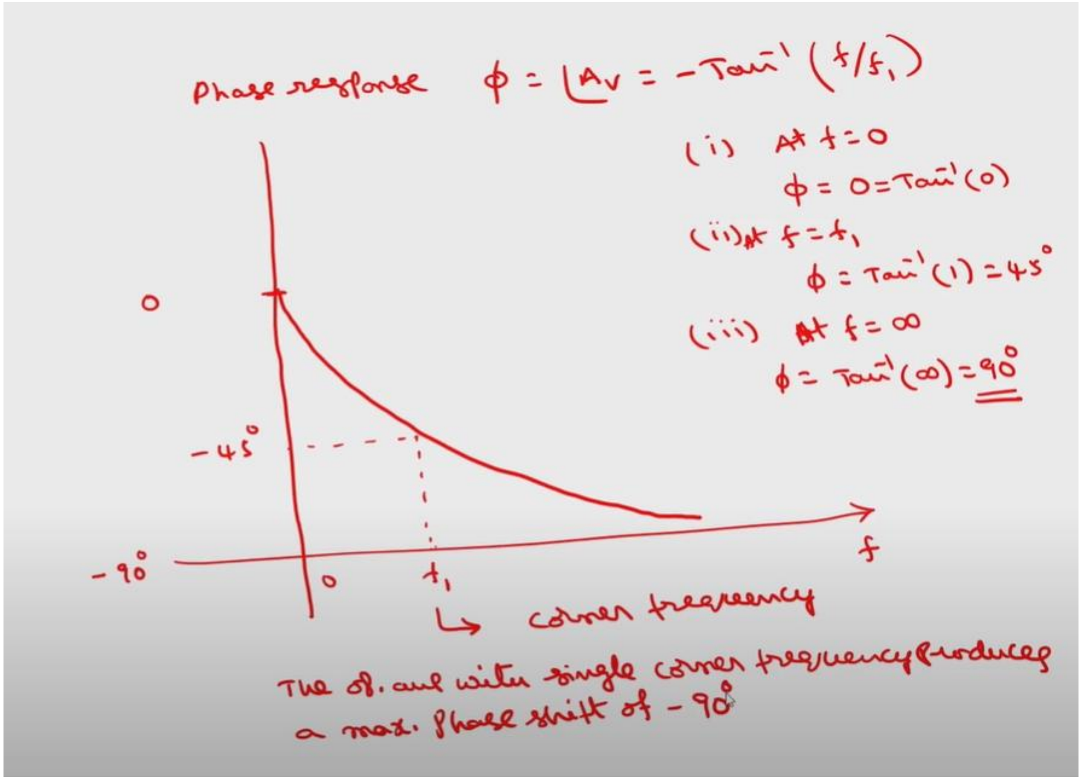
(Refer to the slide at 16:04)



This is expression for the phase, this is the expression for the magnitude. So, here the three characteristics of the amplitude response. Now, what are the characteristics of the phase response? Phase $\phi = \angle A_v = -tan^{-1}(\frac{f}{f_1})$. At $f = 0$, $tan^{-1}(0) = 0$, this becomes $\angle\phi = 0$, this is -90^o , if I take this as 0. So, here at $f = 0$, this is 0.

At $f = f_1$, $\phi = tan^{-1}(1) = 45^o$, and at $f = \infty$, $\phi = tan^{-1}(\infty) = 90^o$, this is tan inverse 0. So, this will be something like this at infinite this will goes to the -90^o whereas, at $f = f_1$ this is -45^o. So, that means, the final conclusion is if the operational amplifier consists of a single capacitance then this will give the maximum phase shift of 90^o and this particular frequency f_1 is called corner frequency. So, the op-amp with single corner frequency produces a maximum phase shift of -90^o. But practically what happens is there will be a lot of number of stages ok, number of stages will be present in the op-amp.

(Refer to the slide at 18:44)



So, in that case what will be the transfer function or what will be the gain? $\frac{A_{OL}}{1+j\frac{f}{f_1}}$, in case of single corner frequency. If I assume that there are three corner frequencies then this will be $1+j\frac{f}{f_1}$, $1+j\frac{f}{f_2}$, $1+j\frac{f}{f_3}$ assuming three corner frequencies. And here also assume that $0 < f_1 < f_2 < f_3$, this f_1, f_2, f_3 are three corner frequencies. Then what will be the frequency response? In case of single corner frequency up to f_1 the gain is almost constant and after f_1 there will be a roll off of $-20dB/dec$. So, in case of three corner frequencies the response will be on the logarithmic scale up to f_1 this will be constant almost.

Then from f_1 to f_2 there will be a roll off of $-20dB/dec$ and after that $-40dB/dec$, after that $-60dB/dec$. If I take this axis here is frequency amplitude. This is $20logA_L$ up to f_1. From f_1 to f_2 this is $-20dB/dec$, from f_2 to f_3 this is $-40dB/dec$, from f_3 to the ending frequency this is $-60dB/dec$. If you go on increasing the corner frequencies then the roll off rate also will be increases.

So, this is $20dB/dec$ for every corner frequency. Now, one of the important parameter here is called as stability operational amplified stability. Operational amplifier will be operated very rarely in open loop configuration. The reason is because of the large gain there is a possibility that the operational amplifier will saturate. So, normally we will operate this operational amplifier in closed loop configuration with some feedback.

So, let us assume that there is a inverting amplifier with negative feedback. This is R_F, this is R_1, this is v_i, this is output v_o, this is equal to $-\frac{R_F}{R_1}v_i$. So, this particular network is called as feedback network. This R_F R_1 is called feedback network and this configuration is called closed loop configuration. So, there is a well-known fact that you might have studied in your feedback amplifiers.

So, the feedback network will reduce the gain of the amplifier. So, if I assume that A is the open loop gain then the closed loop gain is equal to $\frac{A}{1+A\beta}$, where A is open loop gain this is closed loop gain, A is open loop gain and β is feedback factor. Here this R_F and R_1 is going to decide the feedback. Now, the stability of this operational amplifier depends upon the roots of this characteristic equation. So, if $1 + A\beta = 0$, what happens to this closed loop gain? A_{CL} becomes infinity.

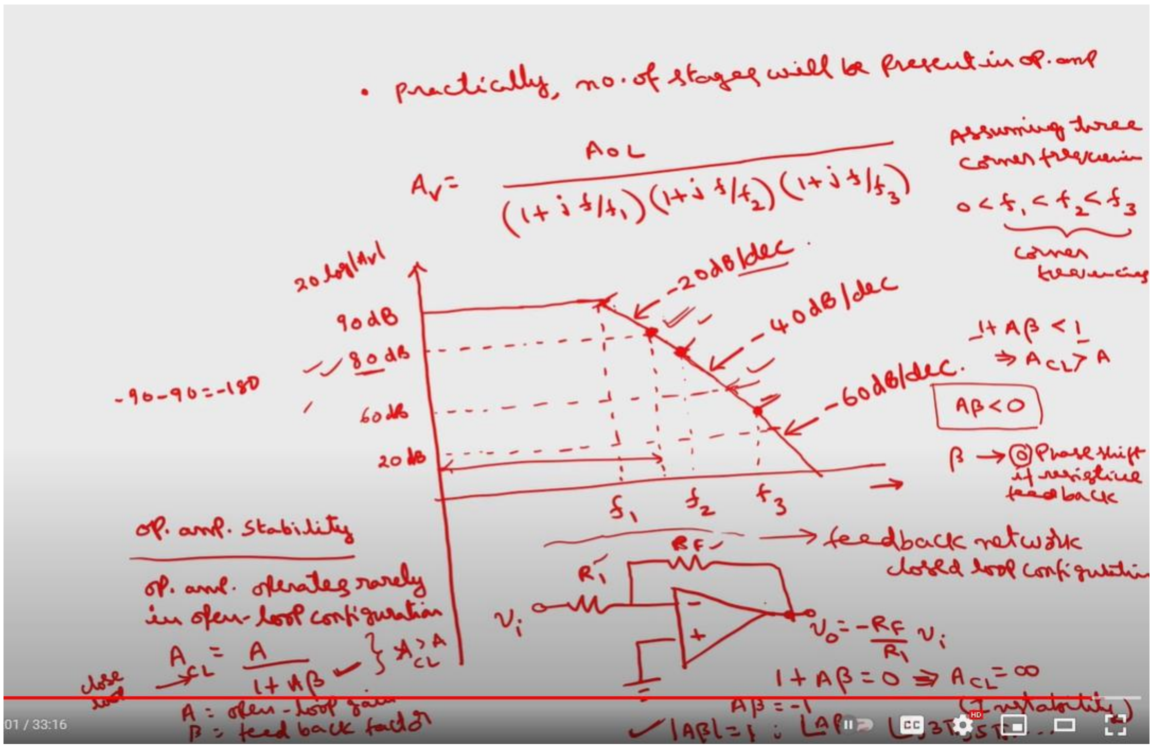
So, this will causes the instability of the circuit. So, in fact, that we are going to discuss in the coming lectures this causes the oscillations of the circuit. So, implies what is $A\beta$? $A\beta = -1$. So, we have the magnitude as unity because $A\beta$ can be complex quantities also. Here of course, you have taken the resistive network, but in general you can have reactive networks also.

So, $A\beta$ can be a complex quantity. So, implies the magnitude of $A\beta = 1$ and phase angle of $A\beta$ should be either π or 3π or 5π and so on. For this condition there will be instability of the operational amplifier, operational amplifier can behave as a oscillator. Now, under what circumstances these two conditions will be satisfied? Magnitude of $A\beta$ is unity and phase angle of $A\beta$ is π or odd multiples of π. So, for that if $A\beta$, $1 + A\beta < 1$, so the denominator of this one is < 1. Means overall this one will be greater than A_{CL} will be greater than A.

So, for this $A_{CL} > A$. So, implies $A\beta < 0$, this 1 1 get cancelled less than 0. So, if $A\beta < 0$ there is a possibility that $A_{CL} > A$. So, this may cause the oscillations or instability of the circuit. So, if I take this resistive network β will not create any phase shift, 0 phase shift caused by the β if resistive network, if resistive feedback. If the feedback circuit consists of capacitors and inductors then there will be a some phase shift caused by β because of the resistive this is 0.

Now, if this A produces phase shift of 180^o or more than that one then there is a possibility that the operational amplifier can be driven into oscillations. So, for that we can easily explain here this through this diagram. So, how many corner frequencies are required to make this system unstable? So, let us assume that this open loop gain is 90dB. So, I want to obtain a closed loop gain of 80dB then what will be corresponding frequency? Let us assume that this frequency is this one. So, this 80dB will falls on to the $-20dB/dec$ line.

(Refer to the slide at 32:04)



So, there will be some bandwidth this is the band of the frequencies that will be allowed for this 80dB closed loop gain. So, here because this point is within this $-20dB/dec$ portion. So, the maximum phase shift that will be caused is -90^o this we have seen in the last slide. So, for a single corner frequency the maximum phase shift that will be caused is -90^o. So, as long as this 80dB falls within this $-20dB/dec$ portion the maximum phase shift is -90^o and this will not cause the system into oscillation it will not affect the stability of the system still the system is stable. So, up to this point system is stable. Suppose if I want a closed loop gain of say 60dB which falls say in this region 60dB so, this falls in this region here this is second corner frequency this is one corner frequency will give maximum of -90^o phase shift the second also may give maximum of -90^o total phase shift becomes minus 90 minus 90 this is minus 180 is the maximum. So, there is a possibility that during this portion up to here there is a possibility that the system may becomes unstable. And if I take this closed loop gain of the order of 20dB if it falls in this region between this f_3 to the last frequency where the roll off rate is $-60dB/dec$ then definitely the system will become unstable because this total phase shift from here to here is totally maximum of 180^o. So, this criterion will be satisfied thereby system becomes unstable. So, that is why how to make sure that how to choose this resistive network and also the closed loop gain such that it will operate in the $-20dB/dec$ region so, that the system becomes stable otherwise there is a possibility of unstability.

So, in case of this unstable system how to compensate this the frequency response because this is going to decrease at rate of $-20dB/dec$ thereby it may affect the stability of the system. To avoid this, we can provide some sort of the compensation frequency compensation. So, this frequency compensation is of two types one is external another is internal. So, we will discuss compensation in the next lecture. Thank you.