Analog ICs

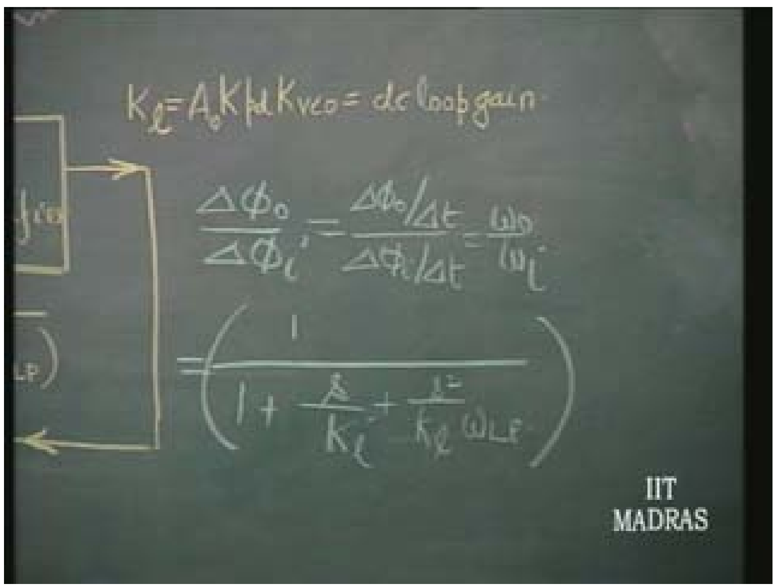
Prof. K. Radhakrishna Rao
Department of Electrical Engineering
Indian Institute of Technology, Madras

Lecture - 25

Phase Locked Loop (continued)

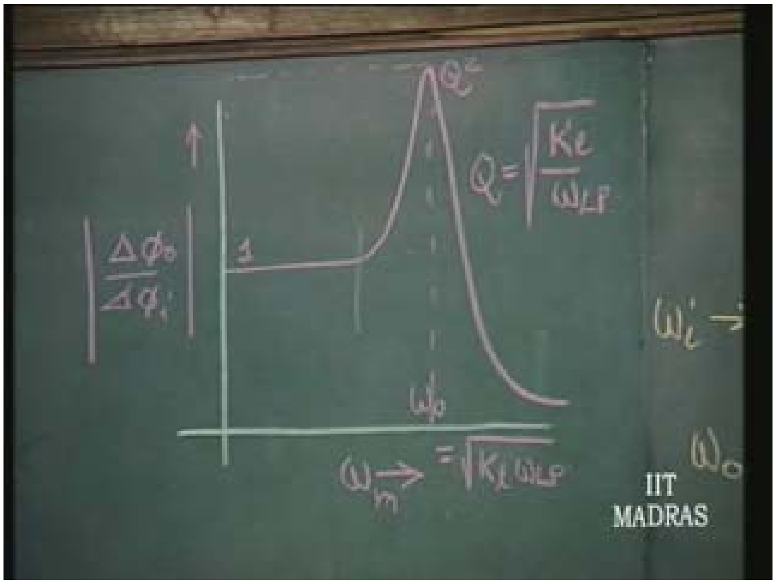
We have just started discussing about how in a Phase Locked Loop we will have output frequency same as input frequency, we have learnt this basic principle. Also, we learnt about how, if we replace these by corresponding sensitivities and transfer functions we can arrive at the overall transfer function which is frequency dependent this frequency being the frequency at which the phase varies. This is emphasized here because there are too many frequencies coming into picture in the analysis and understanding of a Phase Locked Loop.

(Refer Slide Time: 00:02:24)



So you must understand this very clearly that this transfer function corresponds to the frequency at which the phase varies. So, if you obtain that transfer function we see that it is 1 by 1 plus s by K_l where K_l being the DC loop gain of the Phase Locked Loop which is K_{VCO} A_0 into K_{pd} s square by K_l omega$_{LP}$ which is typically representative of a high Q low pass transfer function which is depicted here. It’s magnitude function as a function of frequency is 1 as it is expected.

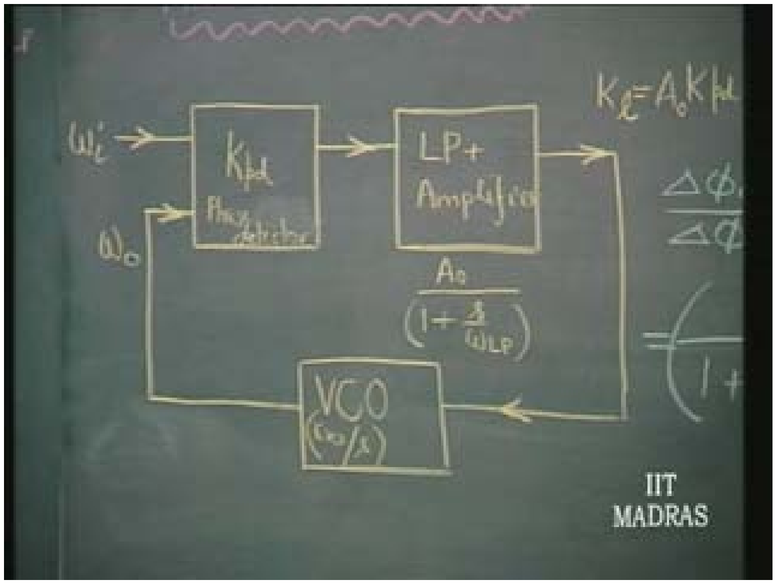
(Refer Slide Time: 00:03:40)



Strictly, phase following is taking place here and there is distortion taking place beyond this range where it is nearing the natural frequency square root K_l into omega$_{LP}$. Therefore it is advisable that you work below this range, it should not go to this range at all otherwise there will be frequency distortion taking place. And for faithful reproduction of the signal which is phase varying is possible only in this range.

And now normally in order that the loop function is satisfactory and the loop gain is high therefore the Q of a typical Phase Locked Loop is going to be high. So a typical Phase Locked Loop is invariably a second order system with high Q pole pair. And there is one reason why we do not attempt to put a better low pass filter here invariably we put at best a first order low pass filter never a second order and all that because the whole system will then become third order and that is definitely going to result in stability problems.

(Refer Slide Time: 00:04:18)

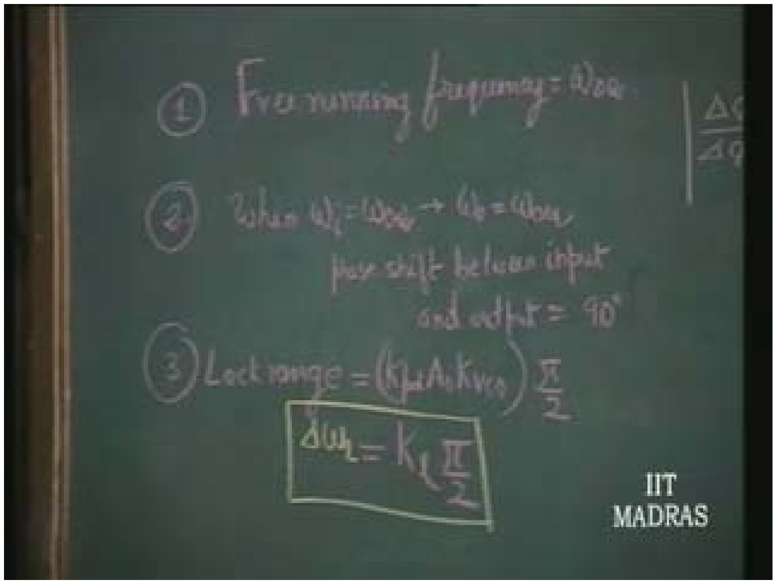


Please remember that this is invariably either a 0th order system wherein the amplifier cutoff frequency itself will do the low pass filtering or a first order system purposely introduced with $omega_{LP}$ being pretty low frequency.

What is free running frequency of a Phase Locked Loop?

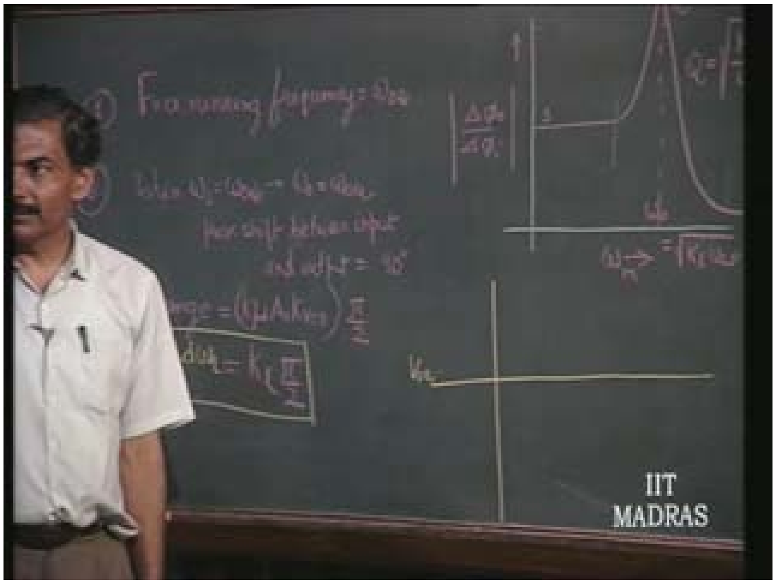
It is that frequency at which VCO of the Phase Locked Loop will continue to run when the incoming frequency is not applied, that is free running frequency. When $omega_i$ is made equal to $omega_{0Q}$ that is when an input is applied now which is the same as the free running frequency then it is obvious that output frequency is the same as input frequency by our scheme of arrangement here. Then there could be a phase between the two inputs to the phase detector and that phase has to be necessarily equal to pi by 2 in order that it sustains the original quiescent voltage here so as to let it continue at $omega_{0Q}$.

(Refer Slide Time: 00:07:33)



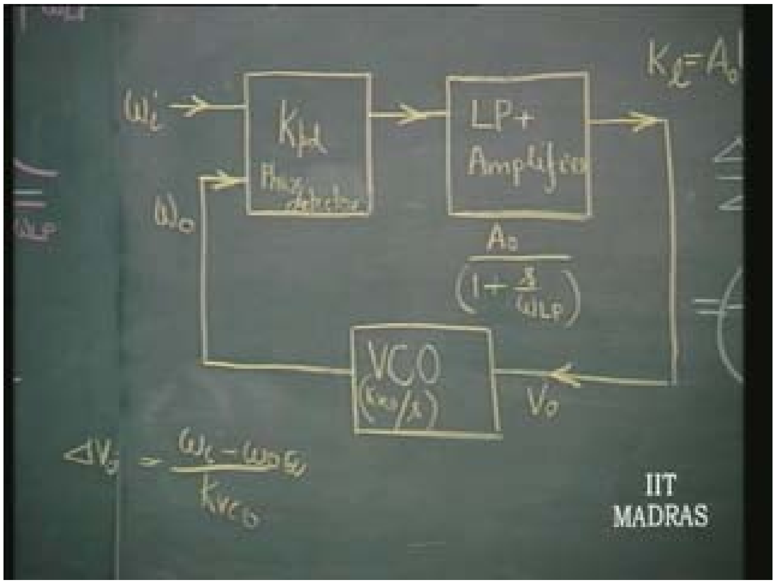
So we have the other important concept here that the quiescent phase shift, when the incoming frequency is omega$_{0Q}$ it is the same as free running frequency 90 degrees. Now from this information we conclude that if phase detector is linear the maximum output voltage that can be obtained here is K_{pd} into pi by 2 then this is going to be amplified by a DC gain of A_0 which is A_0 into K_{pd} into pi by 2 and that DC voltage is going to cause a maximum frequency deviation of K_{VCO} into A_0 into K_{pd} into pi by 2. That is the maximum range over which the VCO can be really strong by this DC voltage. Therefore the lock range is, the VCO is capable of oscillating all the way up to that if the amplifier is not getting saturated in that region and if this output is also not getting saturated in that region then the dynamic range of operation for the Phase Locked Loop to lock is corresponding to delta omega$_L$ which is the lock range which is nothing but K_l into pi by 2.

(Refer Slide Time: 00:07:53)



If we were to look at this DC voltage this voltage will be at V_{0Q} the DC voltage and it is going to vary around V_{0Q} in a linear fashion because if this is $omega_i$ which is not same as $omega_{0Q}$ then $omega_i$ minus $omega_{0Q}$ is a deviation so if this is $omega_i$ which is different from $omega_{0Q}$ then the deviation for $omega_{0Q}$ is this and that divided by K_{VCO} with the change in voltage in this point so that is the delta V_0.

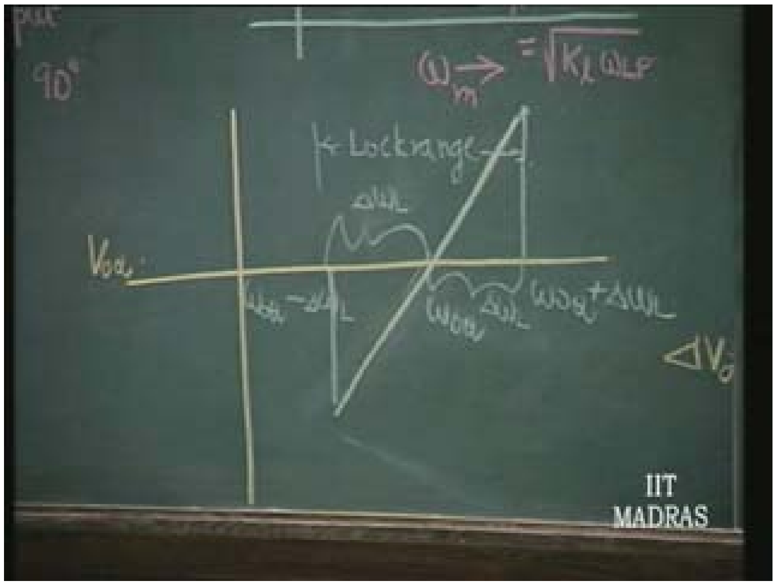
(Refer Slide Time: 00:08:47)



If I am applying an $omega_i$ which is different from $omega_{0Q}$ then the frequency deviation that is necessary is $omega_i$ minus $omega_{0Q}$ that is produced by a DC voltage variation from V_{0Q} by this amount $omega_i$ minus $omega_{0Q}$. That can be above V_{0Q} or below V_{0Q}

depending upon whether your $omega_0$ is higher than $omega_{0Q}$ or lower that $omega_{0Q}$ in which case obviously you will have a linearly varying voltage here and it will go on up to omega si this will go on up to a point corresponding to delta $omega_L$ on this side and delta $omega_L$ on this side strictly speaking and this is the lock range.

(Refer Slide Time: 00:10:35)



Therefore if you say that this is $omega_{0Q}$ this will be $omega_{0Q}$ plus delta $omega_L$ and this will be $omega_{0Q}$ minus delta $omega_L$. So this entire range is the lock range. What is the slope of this? It is 1 by K_{VCO}. This is the characteristic that you would obtain if you where to put a DC volt meter here and keep on changing the $omega_i$.

Now let us consider the situation this way. What we had done earlier was to depict the situation somewhat in an illustrative fashion. I come very close to him and say it is a tiresome affair listening to this lecture, let us go to the canteen and have a cup of coffee or so. He immediately agrees and I entertain him as I walk along with him so that he suddenly does not vanish. I got caught with this fellow, coffee or no coffee I do not want any more of him. So I have to keep entertaining him throughout and hopefully he is sort of listening to what I am saying and he is attentive etc. So I have his span of attention without any disturbance up to the canteen and that is the limit because he knows already once he takes the stuff there he vanishes. That is the ability of my conversation or lecture, the lock range. This is very simple because I have initially captured him there is no way of escaping. He is very close to me and he has to come with me. I can take him up to canteen or any other place even outside maybe Velachery. It just depends upon the range which is already available to me, this is different. This is known as lock. Once it is locked he is under my control, I can take him wherever I want, it depends upon my ability only.

Now let us understand what is capture?
It is a different thing. $omega_i$ is not starting with $omega_{0Q}$. That is, I have not come to him and captured his interest initially. $omega_i$ is far away from $omega_{0Q}$. He is actually

standing near the canteen trying to get an opportunity to catch somebody to go into the canteen. But I want to take him because I want somebody to listen to my lectures so I keep calling his name.

Now there are different things. Capture of attention is what is needed. What are the things that are necessary to capture his interest? My voice should be loud enough to be heard by him. That means his sensitivity as well as my loudness both are factors which are important and then noise, lot of noise is going on there. So it has to be going above the noise in order to capture his interest. That means there are lots of factors which are necessarily to be brought in first to capture itself. Now let us understand in terms of this circuit.

$Omega_0$ is equal to $omega_{0Q}$ when nothing is applied. But now when I am applying I am applying $omega_i$ far different from $omega_{0Q}$. That means I am starting at a point which is very far here. Far means either this side or that side, now what happens?
$omega_i$ is far different from $omega_{0Q}$ the output product is going to be $omega_i$ minus $omega_{0Q}$ which itself is a very high frequency. $omega_i$ minus $omega_{0Q}$ itself is a very high frequency which cannot be permitted by the low pass filter to FBR here. So this will result in no change response at the output of the amplifier plus low pass filter which will mean that this is not going to change. It will continue to free run at $omega_{0Q}$ which means these things will be making some impression but noting comes here. That means in spite of my shouting with all my energy and in spite of his hearing being perfectly the distance is so far away that there is no response that is elicited from here. I shout, he is not so far away from the canteen, he is coming towards this building. Therefore now the chances of capture, the probability of capture is increasing. This $omega_i$ is coming close to $omega_{0Q}$ this frequency is decreasing the amplitude of variation here is increasing.

The VCO is now changing its frequency around its $omega_{0Q}$, on either side it is going higher as well as lower, still capture will not take place because VCO has not been able to become equal to the frequency of the VCO when it is changing. It is never trying to become equal to $omega_i$ because $omega_i$ is still far away or the change that has been produced at the output of the VCO is still not large enough. It is like this, you have some oscillation taking place, you can think of a trick that is played with a chimpanzee normally in a zoo. The chimpanzee is supposed to be a very intelligent animal. They try all sorts of things to test the intelligence of the chimpanzee. One of those is this, it does not have much work to do but it always wants to do something or the other, some mischief kind of a thing. So they put up a sort of rope through a pulley and at the end of the rope they tied bananas. So it was just speculating as to how it can catch the banana. It looked at the height. It knows its capability, it did not even attempt, it felt that it is too high, I am not going to jump. It has already decided so it does not even attempt.

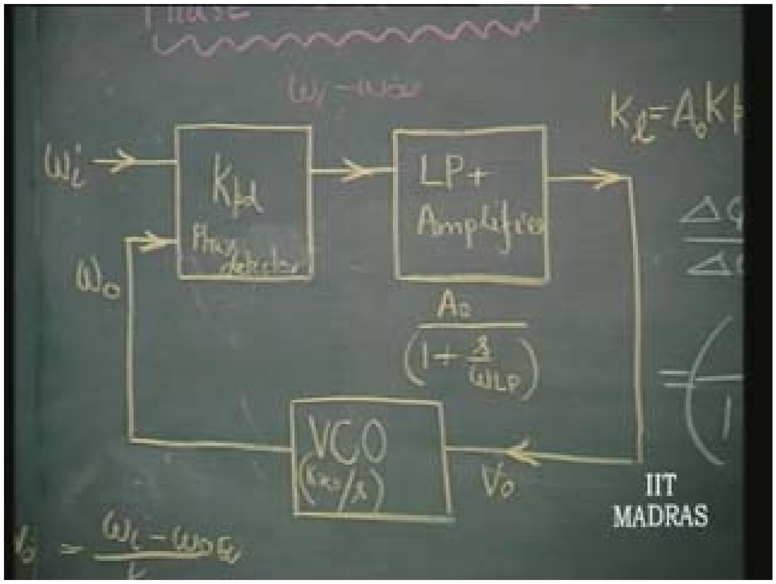
Now what these people did was they started making it go up and down. It still started looking at it, but still did not jump mainly because the up and down motion even though was indicating that it is coming down it knows that it cannot jump up to that extent as to at any given time to catch the banana there. Then they increased the amplitude of oscillation. Now it started moving slowly when it has estimated that its ability such that there is a possibility of it catching, it knows at sometime so it also starts jumping. Now it is a trial and error question. When it is coming down it should jump up. So it learns by experience so it keeps on trying to synchronize the frequency in such a manner that whenever it is coming down only then it is jumping up.

Ultimately the story is that it captured the banana. Once it gets hold of it then there is no chance of dropping it and that is the process of capture in a nut shell. The moment this voltage starts changing this frequency starts changing. Now this is not such a simple concept in the sense. When this frequency starts changing I can no longer say that it is changing around omega$_{0Q}$ because it is changing at every instant of time. So what is happening is, this is changing and if it is a negative feedback system it should change in such a manner as to ultimately become equal to omega$_i$. That means it should be keeping on producing a DC here which will be in such a direction as to bring omega$_0$ ultimately to a study state of omega0 becoming is equal to omega$_i$. This is what happens in the case of capture.

It is a totally nonlinear process but as a first order of approximation what I am trying to do is assume that this is remaining at omega$_{0Q}$ in spite of it changing around omega$_{0Q}$ then I am telling that the probability of capture is going to be there only when this is swinging in such a manner up and down and when at any given instant of time the frequency is capable of becoming equal to omega$_i$ at least. That is the same story of monkey wherein the banana is brought down to that extent where this maximum effort is going to take it to that. Then it is probable that it is going to catch hold of the banana, otherwise it is not. So, the capture range is that range when this frequency just becomes equal to the incoming frequency.

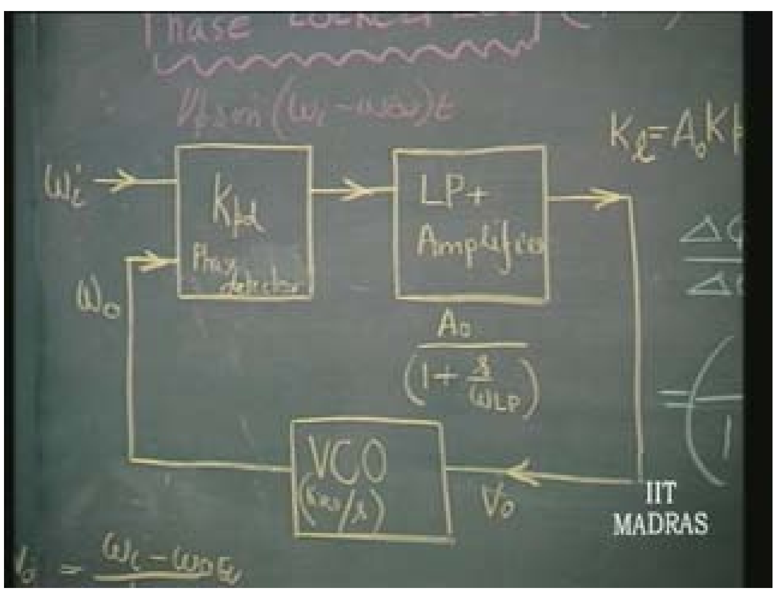
Let us therefore make several approximations here and the approximation is good enough most of the time to understand this capture phenomena. The actual theory is beyond the scope of this lecture that is very well given in a book on Phase Locked Loop by Gardner. But then it is not necessary to understand the actual theory at all because the actual theory also gives you not a very accurate result because of the assumptions made etc.

(Refer Slide Time: 00:23:12)



This is good enough for us to understand about capture range, omega$_i$ minus omega$_{0Q}$ is the frequency output here. If that is the case I am assuming that this is sinusoidal output, it is not. This omega$_i$ minus omega$_{0Q}$ is not a constant frequency, it is changing omega$_i$ minus omega$_0$ actually it is not omega$_{0Q}$. And it is not a sine wave because it is just limited at the top and the bottom. It is a square wave kind of thing changing in frequency.

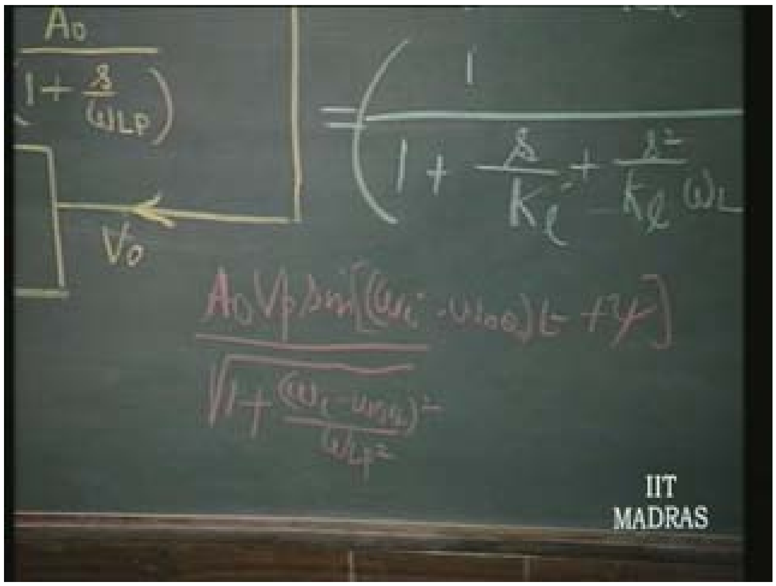
(Refer Slide Time: 00:23.45)



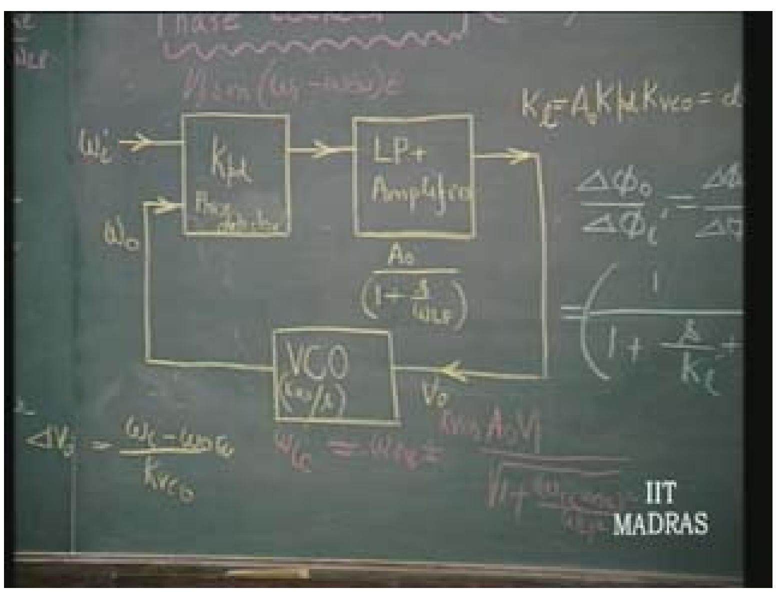
Therefore I am just assuming that it is V_p sine for simplicity. Suppose it is that then the amplitude of this output is going to be passed through a low pass filter and amplification, here this is the V_p sine omega t. So it will be A_0V_p sine omega$_i$ minus omega$_{0Q}$ t plus s$_i$

by square root 1 plus $omega_i$ minus $omega_{0Q}$ square by $omega_{LP}$ square. That is the attenuation this amplitude here suffers and that multiplied by K_{VCO} is the frequency deviation around $omega_{0Q}$. This is the voltage change and that into K_{VCO} is the frequency deviation around $omega_{0Q}$. That means this frequency is going to change around $omega_{0Q}$ by this magnitude on this side maximum because it is sine something so I do not have to worry about that this maximum value is 1. So the deviation is at best equal to $omega_{0Q}$ plus this, these are the limits $omega_{0Q}$ minus this and that should at least become equal to $omega_i$ and this is the capture range.

(Refer Slide Time: 00:24:48)

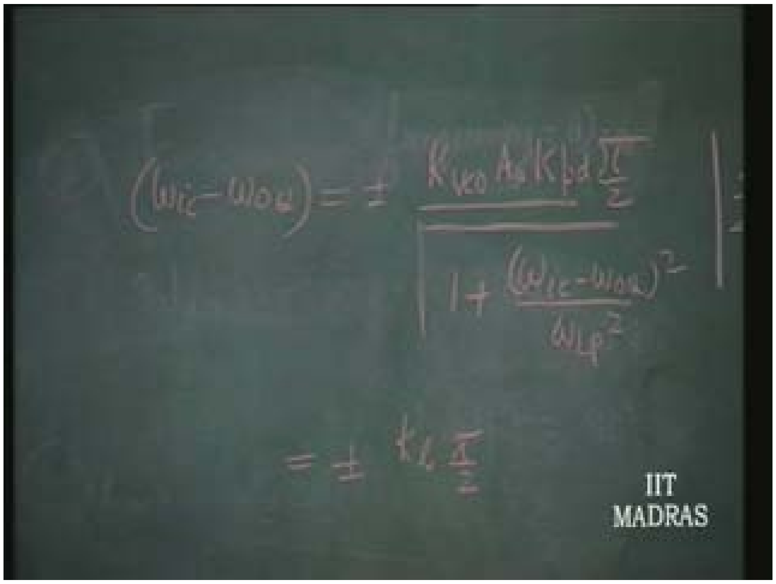


(Refer Slide Time: 25:35)

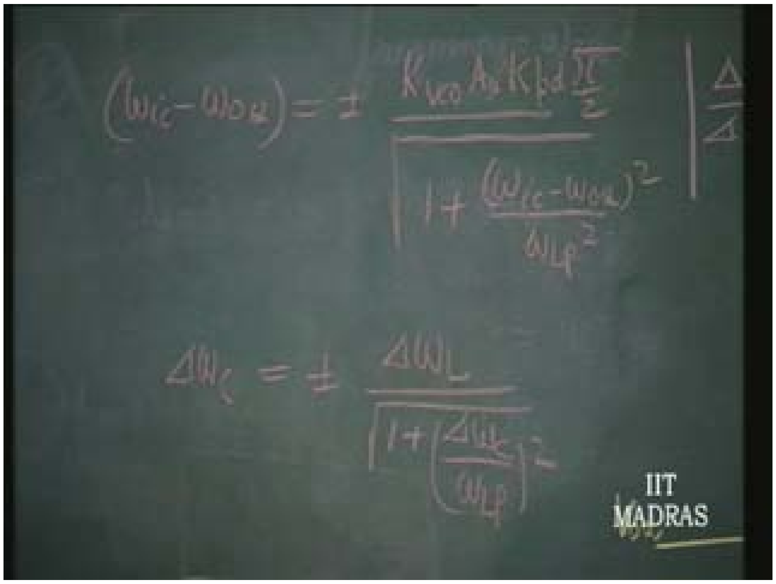


That limiting frequency is the capture range from which we can now get $omega_{ic}$ minus $omega_{0Q}$ is equal to plus minus K_{VCO} A_0 V_p what is it called already we have been calling it as K_{VCO} A_0 V_p is nothing but V_p is the maximum DC voltage variation possible at the phase detector output which is nothing but K_{pd} into pi by 2 if the phase detector is linear. Therefore, the maximum DC is nothing but K_{VCO} A_0 V_p is K_{pd} into pi by 2 by square root 1 plus ($omega_{ic}$ minus $omega_{0Q}$) square.

(Refer Slide Time: 00:26:59)



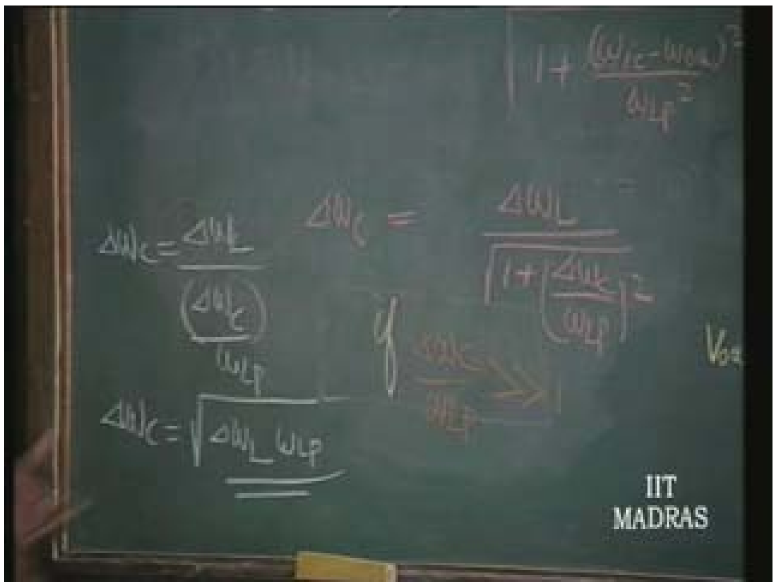
(Refer Slide Time: 00:27:26)



This is nothing but plus or minus K_l into pi by 2. And what is K_l into pi by 2?

That is delta omega$_L$. We will call this omega$_{ic}$ minus omega$_{0Q}$ as delta omega$_C$ capture range around omega$_{0Q}$. So (delta omega$_C$ by omega$_{LP}$) square is nothing but delta omega$_C$. Since it is the capture range we do not have to bother about this and this is the equation for lock range in general. It is the quadratic equation in delta omega$_C$ and if delta omega$_C$ by omega$_{LP}$ is very large compared to 1, if delta omega$_C$ be omega$_{LP}$ and omega$_{LP}$ is the low pass filter cutoff frequency, if delta omega$_C$ by omega$_{LP}$ is much greater than 1 then for that condition alone what happens here is this delta omega$_C$ is equal to delta omega$_L$ by delta omega$_C$ by omega$_{LP}$. Or delta omega$_C$ is equal to square rootdelta omega$_L$ into omega$_{LP}$.

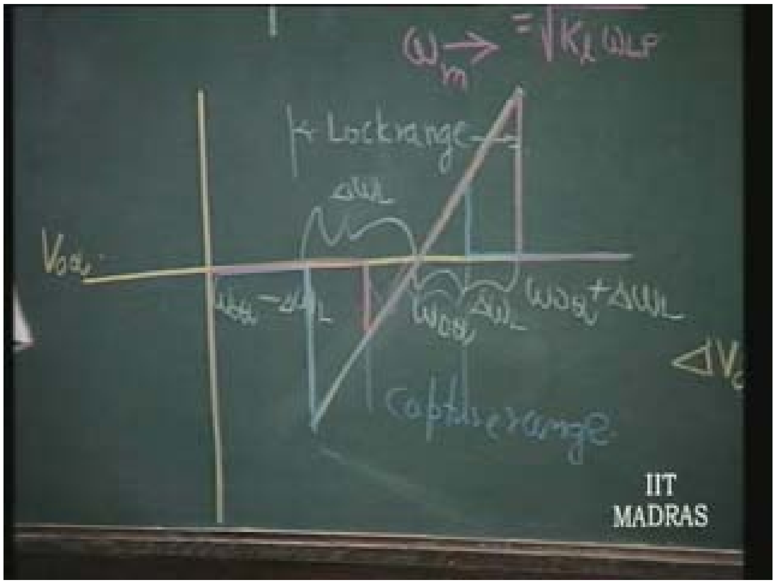
(Refer Slide Time: 00:28:42)



Normally if delta omega$_C$ by delta LP is much greater than 1 you can straight away assume that delta omega$_C$ is square root delta omega$_L$ into omega$_{LP}$. After obtaining this delta omega$_C$ you have to verify whether delta omega$_C$ by omega$_{LP}$ is much greater than 1. If that is holding good then you are lucky otherwise you have to solve the quadratic equation but do not straight away solve the quadratic equation. You straight away assume that delta omega$_C$ is root of this and verify whether thereafter this is getting satisfied. If this is getting satisfied you need not solve the quadratic equation otherwise solve the quadratic equation, take the appropriate value for delta omega$_C$ which is the capture range.

Capture range is obviously less than the lock range. Now how does capture takes place?
It is like this. It is going on coming close to omega$_{0Q}$ it will come very close and at a certain point this swing has become just sufficient to capture omega$_i$ at which point it will jump then you say it is captured.

(Refer Slide Time: 00:31:15)



And now after I capture his attention as I told you I can take him with me anywhere in the locked range. Now it will go out of lock so this is the way it will behave when you come from this side. If you have to come from this side it will go on then it will get captured as it comes close to this capture range and then it will go on and on. This range is called the capture range. Within this if it exists initially then immediately capture will take place. Capture is highly likely to take place. The probability of capture is very high.

Now obviously capture requires this probability that it is going to at least become equal to this. Then if there are two persons obviously let us say, he is there and she is also there, they are together at the same distance. I shout and he hears my voice but she does not here my voice. Therefore obviously it is dependent upon hearing ability of the individuals there. The same way I have two signals which are pretty close one stronger than the other obviously the stronger signal is the one which is able to elicit response from me when other things remain the same. This phenomenon of capture is very important in Phase Locked Loop.

You can make this capture range as narrow as you please by selecting omega$_{LP}$ as small as possible which is under your control. Make omega$_{LP}$ very small and then you can make the capture range as small as you please. Therefore this can be made a narrow band high Q filter. As we see when omega$_{LP}$ is made very low queue of the system is make being make very high. And using such system you can make queues of the order of thousands or tens of thousand very easily. It becomes pretty difficult to actually realize such high Qs in other systems by using other conventional techniques.

This is a very important selective circuit. Out of that many signals coming to the input it can select the signal automatically. This input is now going to comprise FM from Madras, FM from maybe somewhere else assuming that there are several FM signals coming here, the carrier, if it corresponds to a frequency which is close to omega$_{0Q}$ only that is going to be selective. The rest of the FMs even though occurring here is going to be rejected. It is going to lock on only to that whose carrier frequency is closest to the free running frequency. Therefore by varying free running frequency I can tune the PLL.

Therefore one way of selecting FM stations or FM reception particularly even when the signal to noise ratio is very poor in the sense lot of noise is there this particular thing can select the FM you require and produce the output here, exactly the same FM but now devoid of all contamination noise, other FM stations as well as other noise gets eliminated out of this and this becomes a signal with higher signal to noise ratio, this is called signal conditioning. This application of Phase Locked Loop is called signal conditioning. Not only that, it has signal to noise flow improvement and this signal strength itself can be at any level you want because this is the VCO output and the VCO output power can be at any power level you design.

This kind of signal conditioning can be adopted in what are called repeater stations where you want to improve the signal strength and then you dump it on to the same line for further transmitting when you think that the signal is weakening. So, improve this and then pass it on to the line signal conditioning which is an important field of application for this. And the Phase Locked Loop is used in most of the FSK signals the Frequency Shift Keying.

All the data from the keyboard to the far off Central Processing Unit or from PC to main frame for all these communication channels you adopt what is called Frequency Shift Keying. Therefore once you have 300HZ and zero set to 400HZ you decide. So the data transmission is going to be converted to FSK signal 1s and 0s that is 300 and 400. And another person says my 1s will be at 500 and 600, 1s and 0s will be 500 and 600. And all of you will decide to use the same transmission line maybe a telephone line. All these go to the Central Processing Unit and there you have to separate it and that is done by PLL invariably.

You put a PLL there and tune it correspondingly, if it is 300 and 400 you will have $omega_{0Q}$ of that to be se selecting this at maybe 350, 500 and 600 may be 550 so that you are capable of producing the 1s and 0s at this point now because this is going to be exactly the replica of the FSK signal that is coming here but this is going to be nothing but DC producing the FSK that means it is nothing but the original data stream straight away. That means this is also called FM detector. That means, if you use it for signal conditioning output is going to be of taken here. If you are going to use it for FM detection the output is going to be taken here so this is also used for FM detection.