Circuits for Analog System Design

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Lecture No. # 34

Design of lock in Amplifier Circuit with example

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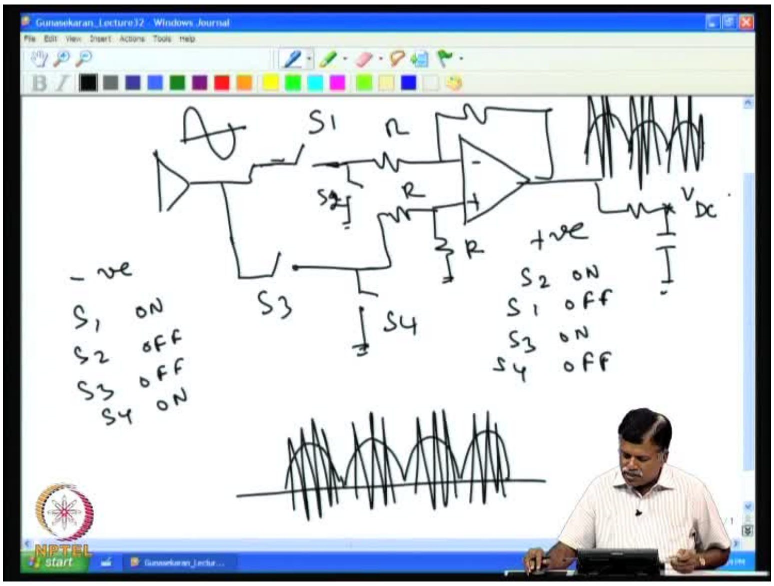

Last class we were discussing about working principle of the lock in amplifier and lock in amplifier is used mainly to remove the noise. And also it is used to separate out in phase and out of phase components. So, we had shown in the previous lecture that how the noise is removed by means of averaging. So, we are shown that you know, we can have switches, you know the use of four switches. We are shown, how to remove the noise which is actually signal which is buried in the noise. We are shown last time that we had these switches ((No audio from 01:1 to 01:17)). So, we have the switches S 1, S 2, S 3 and S 4. So, we have the difference amplifier here.

When the signal here going positive or negative so, when the signal is positive here. When the signal is positive, you want the output to be positive, then at that time switch on S 3, switch off S 4. So that, whatever signals coming it, comes here at that time we switch on S 2, so at positive when this signal is positive - S 2 on, S 1 off and then, S 3 on and S 4 off. So, the positive signal appears as it is and then, we do the reverse of this when the signal is negative. When the signal input is negative, then we want whatever signal that is coming here, that is to be applied here and inverted and is put here. So that, inverted become again positive for that we switch on S 1, we make S 1 on, S 2 off, S 3 off, S 4 on.

So, the minus voltages whatever is coming here that appears here and it is getting inverted, and inverted voltage become again positive at the output. So, you will get signal like this. If noise is there noise, which is positive or negative whatever was there at that time that appears as it is. Because these switches are actually not like diode, they allow both signal positive as well as negative values together. But we are operating this, we allowing the signal to go, when the signal is minus. At that time, whatever signal the noise is there which is positive or negative that also comes and appearing at the output.

So, because of that you will get output which contains typically signal, which are actually always put at positive sign and the noise whatever was there which may be positive or negative. So, that is how it appears at the output and net result is if the output is filtered, then that will have only the DC voltage proportional to noise. So, V D C is proportional to noise and this is the time constant select such that, time constant of this R C time constant much larger than the noise frequency that we are encountering. Probably, the lowest noise frequency, lowest noise frequency can be compared with this RC time constant.

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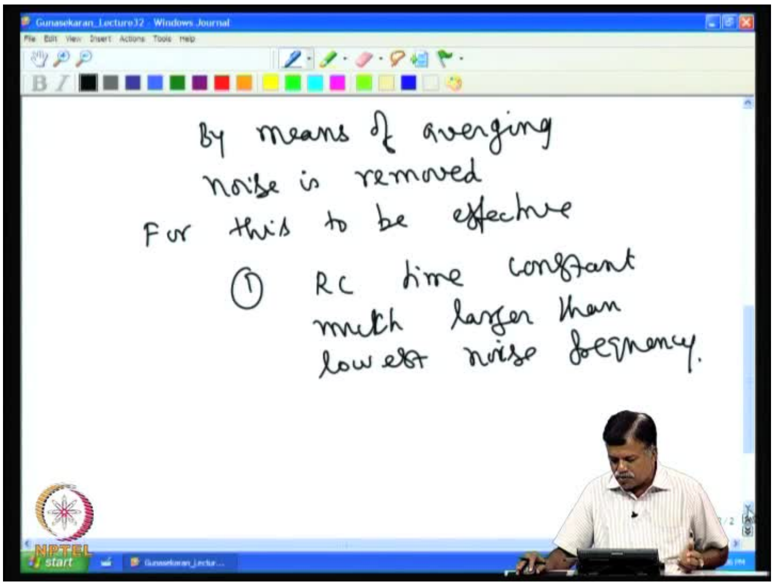

So, by means of averaging by means of averaging noise is removed. For this to be effective for this to be effective we need R C time constant, R C time constant much larger than lowest noise, lowest noise frequency. This is how the lock in amplifier works. Let us see before getting into the actual lock in design, we will see what is the other use of the lock in amplifier? Other use of the lock in amplifier is separating out the in phase and out of phase component. That is required at many places, because in phase and out of phase component get mixed up.

If we are for example, resistance and capacitor together are, inductor and resistance together are both LCR combined, also can have in phase and out of phase components mixed together. It is essential to separate out. For example, R and C in R C circuit that is what is the value of resistance, what is the value of capacitance can be separately find out using the lock in principle.

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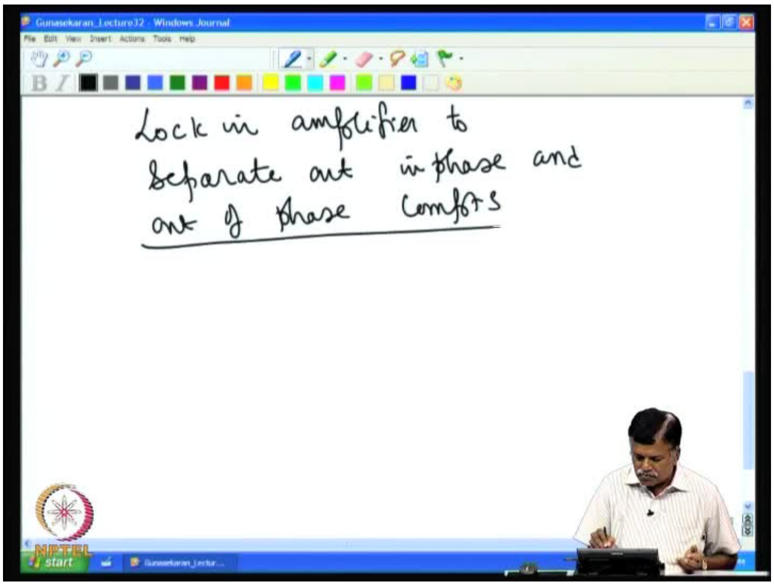

Let us see, what is the basic concept involved in separating out in phase and out of phase component? So, lock in amplifier to separate out, separate out in phase and out of phase components. ((No audio from 06:31 to 06:44))

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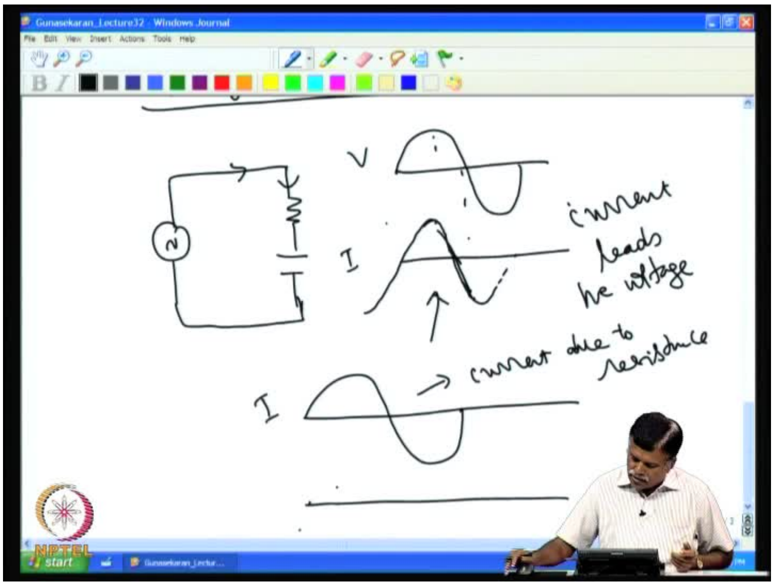

Because if I have for example, A C source and then, if I have R C circuit for example I can have R and then C. Now if I look at the current through this current and this voltage so, the voltage at this point and then the current through this, they will have a phase shift. It had been a pure resistance and the current and voltage will have been in phase.

Now there will be a phase shift between this current and this voltage, in this case current would be leading and the voltage will be lagging actually. So, you will have for example, this is the voltage at zero, you will have current leading. So, you will have already current actually leading and the current reaches maximum at this point. You have for example, in ninety degree components you will have this and then, this actually peak occurs nearly at zero point.

So, you have a phase shift of course, the phase shift need not be ninety degree. So, here the current leads the voltage. Now, if you want to measure the capacitance resistance separately, then I should it is possible to separate out the in phase and out of phase components. This I can reconstruct this by superimposing two waves that is the resistance gives in phase component, which is in phase with the voltage. And then, the capacitor gives me the current which is ninety degree, this is the current due to resistance. This current due to capacitance, capacitor current will be leading ninety degree. So, you will have at this point, the redraw the…

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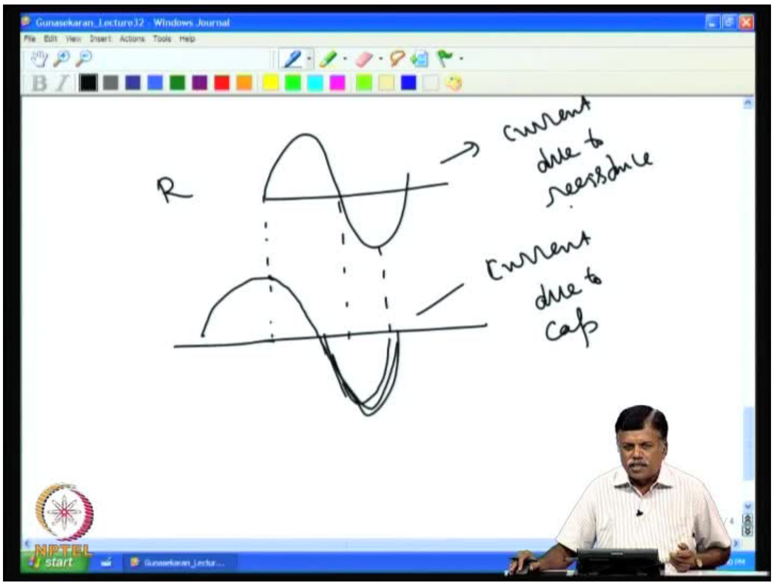

So, you will have resistance component gives this kind of current, this R and then the capacitive part actually will have leading amplitude. So, current would be maximum here and then, it is come back to zero in case of and then, at 0 it goes minus maximum and again at peak it comes to zero. So, you will have this is actually due to current due to capacitance, this is current due to resistance.

We can superimpose this and get the resultant waveform, resultant current waveform. That is what happens? So, one if I can separate out the in phase and out of phase component that it is possible to measure the resistance and capacitance separately.

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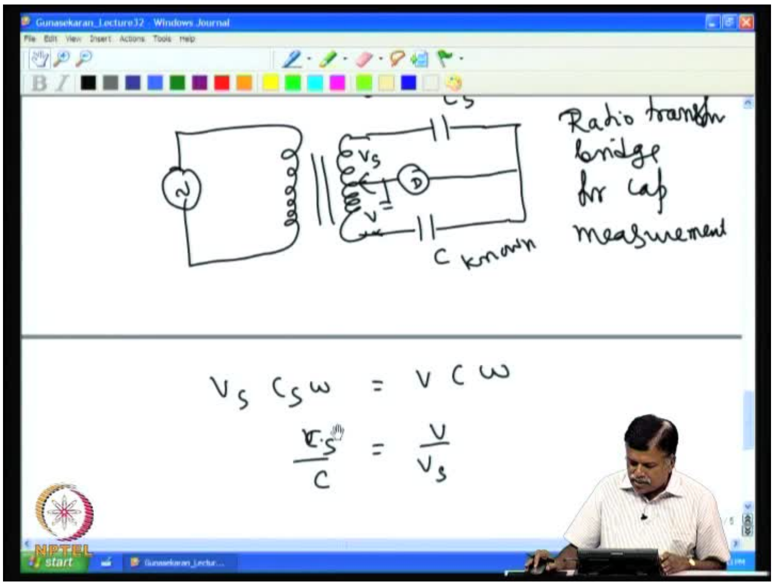

For example, we had discussed earlier what the use of ratio Transformer Bridge. So, there in we had transformer like this and then, we had secondary with tapping. And then, capacitor should be measured we put the capacitor here and then, we have connected the detector here. This I had explained you earlier that how this avoids various stray capacitances? Now, we see how the lock in amplifier can be effectively used in this case. So, this is the ratio transformer bridge, the ratio transformer bridge for capacitance measurement.

Now, assume that this you know actual balancing, we will see for example, this is unknown capacitor C sample and this is unknown capacitor C then we have this V S here. And then, V the voltage that is with respect to ground, what is the voltage here? what is the voltage here? Actual working principle is that the voltage this V actually drives the current like this; the V S has actually drives the current to detector like this, and the V drives the opposite current in the reverse direction. If these two currents, you know current given by this and the current given by this are equal, then you will get a null at the detector.

So, by knowing V by V S, one can find the ratio of the actual balancing point that is the current through C S will be given by V S, the current through C S is given by V S into C S omega and that should be equal to V into C omega should be given. So, that comes out C S by C comes out to be V by V S. So, once I know if I know C the known value C, this is known value you know the value of C and V S and V is known. So, C is known, in this case C is known and V and V S are known, so C S can be determined. Now in this case, a simple detector will do, but unfortunately in real life these capacitors may not be ideal capacitors. The capacitor may have its own resistance.

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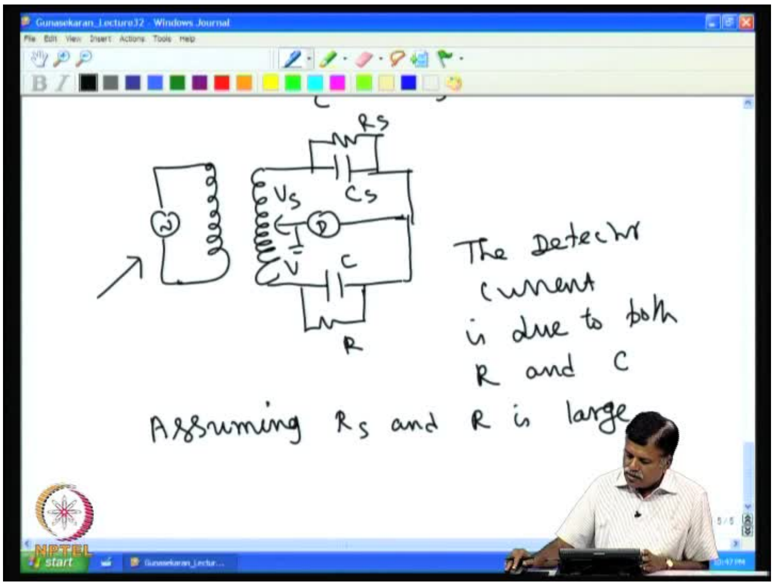

So, let us see the real life situation that we have an AC voltage applied here and then, we had the ratio transformer, this is the center tapped. Then, you have this resistance assume that this is having a resistance here. Then, will have another component and this resistance also to be introduced. Now, if this is the sample and then this is R S and this is C and then, this is R.

Now the detector will balance the detector current, detector current is due to both R and C due to both R and C. Now, it will balance only both resistive component and the capacitive component equally balances out. Now that would be difficult, because if you see that you know if I vary this one, it varies both this voltage for example, if I have V S and V. So, if I vary the center tap, then V S changes, V also changes. But it can balance only one component that is either C or R, not both.

If I have a detector, assume that if I have a detector which detects only in phase component, in phase with applied voltage. For example, if this is the applied voltage, if I have a detector which is sensitive to detect only the component which is in phase with this. Then, at that time I can balance only R, by varying this I can balance R. Suppose, I keep this detector which is sensitive to 90 degree out of phase. Assume that detects only 90 degree out of phase components with respect to applied signal, then I can balance C capacitance by adjusting this. So, one can balance separately R S and R. In this case, if assumes that R S that leakage, the shunt in the R S and R are very high; if it is very small, then will have other set of problems and we have to modify this one.

There are ratio transformers bridges called double resistance transformer bridges and so on, but we will not get into this. Here we assume R S and R are very large, but still it is a considerable amount when capacitors are very small. So, under this assumption, let us see how the lock in amplifier can be utilized here to balance the bridge that is to separate out in phase and out of phase components. So, assuming R S and R is large.

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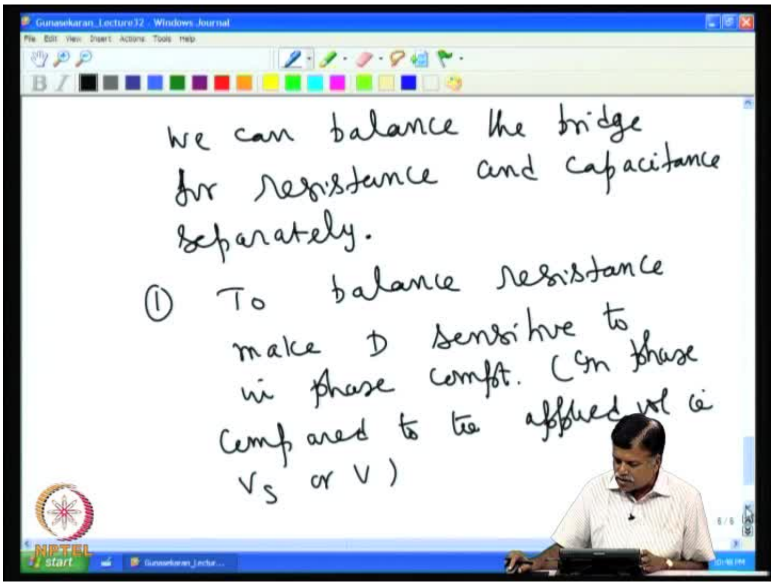

We can balance the bridge we can balance the bridge for resistance, for resistance and capacitance separately ((No audio from 16:36 to 16:45)). Now, first to balance resistance, to balance resistance make D sensitive to sensitive to in phase component. There is in phase compare to the compare to the applied voltage in phase compare to the compare to the applied voltage. That is V S or V.

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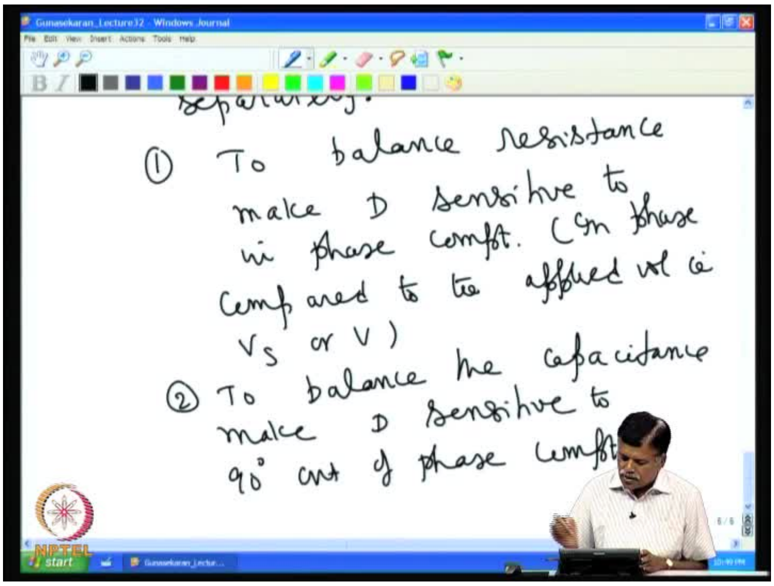

Similarly, to balance the capacitance, to balance the capacitance to balance the capacitance make D, make D sensitive to 90 degree out of phase component out of phase component.

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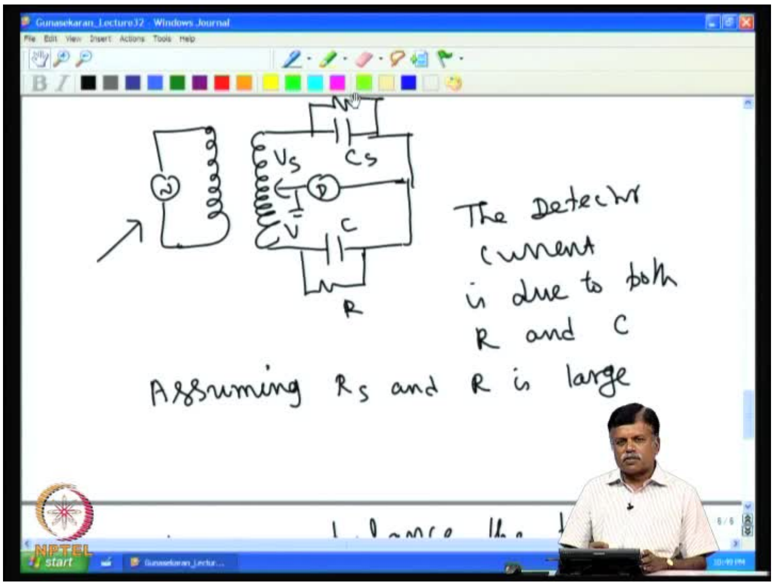

Then, one can balance out resistance and capacitance separately. So, if I keep this one sensitive to 90 degree out of phase component with respect to the V S, R with respect to the input voltage. Then, this I can vary the center tap to balance capacitor alone. It will ignore the resistance part very less volt, because this detector is not sensitive to in phase component. So for example, if I want myself capacitance and make it sensitive out of phase component, and then vary this so, you will get capacitive measured. Then make this D sensitive to in phase component, now balance and get the resistance value. So, this detector now describes lock in amplifier, this detector can be a lock in amplifier. Let us see, how to make it sensitive for in phase and out of phase component?

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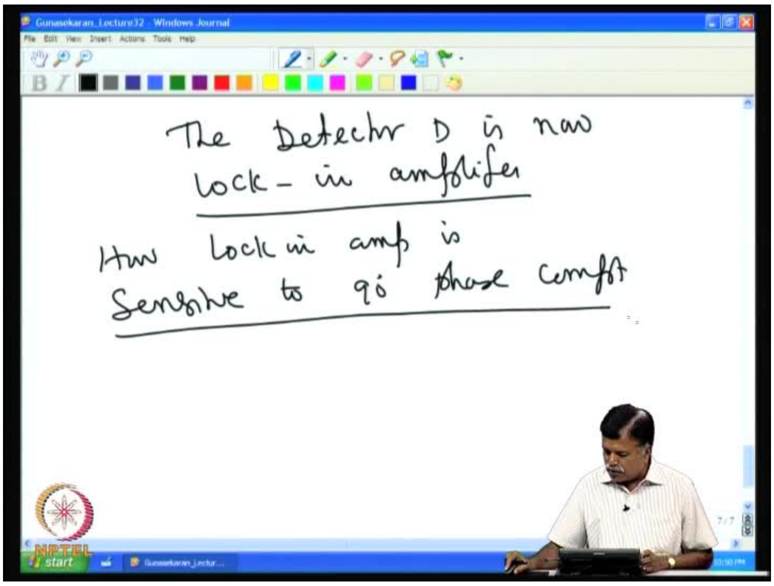

The D is detector D is now locking in amplifier. So, let us see, how the lock in amplifier is sensitive to in phase and out of phase component? So, how lock in amplifier is sensitive to 90 degree phase component? Now this can be achieved in the following manner.

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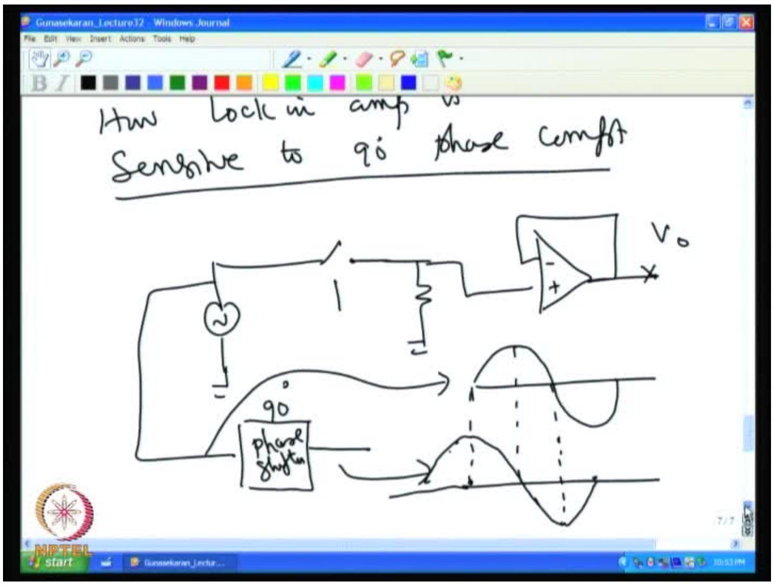

Like we have seen the switches, now I take a simple case that we have a signal source here then, we have a switch here. Then assume that we had input here, assume that output there, source here connect the signal at the output. Now we have to operate the switch, now assume that I put here the analog switch or assume that this is the analog switch. And then, I give a gate signal to this to make it on or off, apply a gate voltage, assume it is on and it is off, when the gate voltage is zero.

If the input signal and the gate signal suppose, if I have input signal like this, then let me have a phase shifter here, we have a phase shifter here which is 90 degree phase shifter. So, basically 90 degree phase shifter I have and then, I take the output. So, this will be the input signal here, and the output here will be 90 degree phase shifted. That means, when it is zero, it is actually high. When it is zero, the input high then when it is high, I will put the points here. So, we get, we start here and then it becomes this leading phase, we will have signal 0 degree have 90 degree phase shift already. Then, it slowly comes back to 0 degree you have to have 90 degree phase shift and then, comes back to zero here and goes back to minus 90 at this point, comes to zero again at this point.

So, you will have a 90 degree phase shift is common coming at this point. So, you will have the signal completed like this. So, output is phase shifted at this point and then, you get a phase shifted output. Now what I do is, I will square this waveform and offer to the switch actually.

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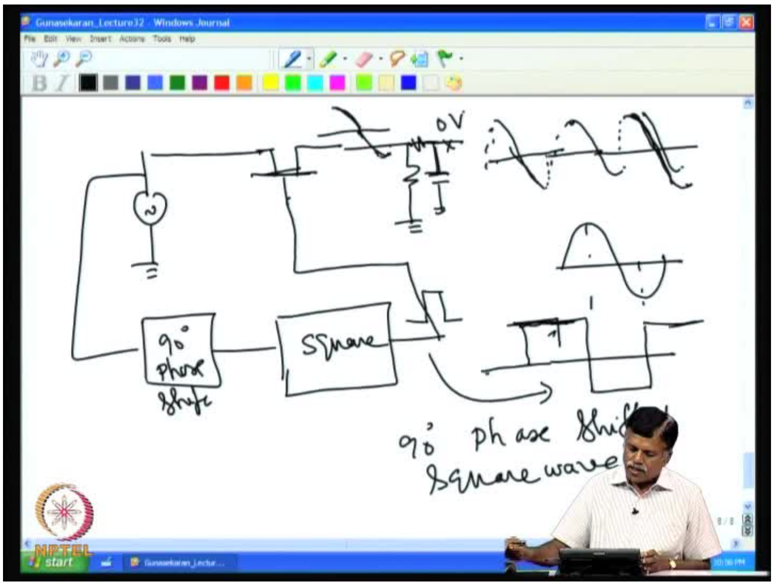

So, what I do is that I will have a signal I will have a signal, then I will give it to the switch. For example, I will put a bilateral FET switch, and then you have the voltage here. Now this I will have a 90 degree phase shifter, 90 degree phase shift then, this I put as squarer; this is converted into square wave. So, you will get square wave which is 90 degree phase shifted compare to the sine wave. So, you will have the two waves if you see that the input sine wave like this and then, you will have the output which is actually phase shifted and square. So, you will have the change occurs at this point.

Again the wave form changes at this point is a 90 degree phase shifted wave so, you will have that is the voltage that you get 90 degree phase shifted phase shifted square wave. This 90 degree phase shifted square wave is given to the switch. For example, then if I look at the voltage at this point, I will get, I will be getting the sine wave like this. You know, because whenever it is on the output is coming so, you have the voltage comes like this. Then you get to know voltage, then other half assumed that negative side it is completely half.

So, during the positive cycle that you will get the signal, other half you will not be having the signal, you will have a signal coming out like this at the output. If you see this half the sine wave is coming, you know other half is lost it is not there you know the switch is not allowing the other half to come. So, you will have signal at this point positive, half of positive and half of negative would be coming here.

Suppose, we have put R C network at this point for example, I put on the R C network this point, then I will get a zero volt. This is because whatever voltage is applied here, 90 degree phase shifted and then we are switching. So, you will get half the sine wave that is you will get the voltage of this part.

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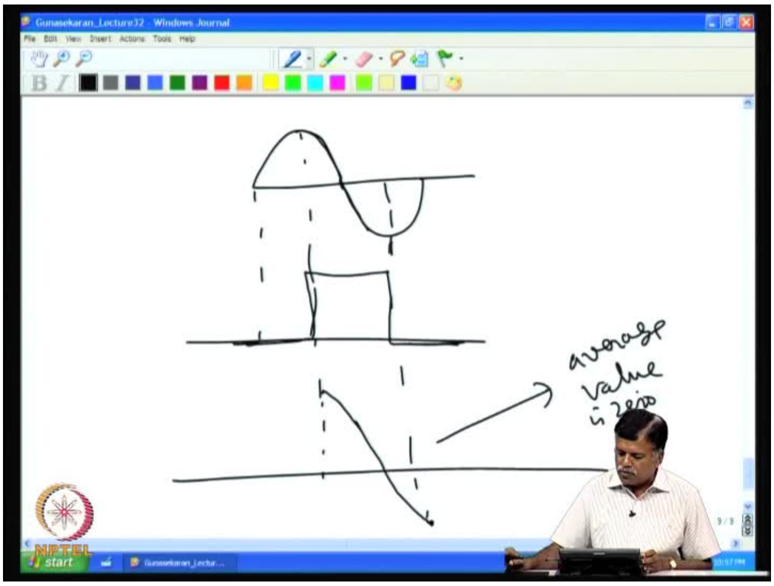

For example, in this case I can show you separately now with… Assume I have a sine wave like this ((No audio from 26:55 to 26:06)) and then I have a square wave which is like this. Now if I operate this, then I will get only this waveform alone will be coming here. So, you will get the output in the switches and that is what it turns out. When it is averaged out, the average value is zero.

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That means, now the signals here this and this are if they are 90 degree out of phase. So, there is no so, the output is actually zero.

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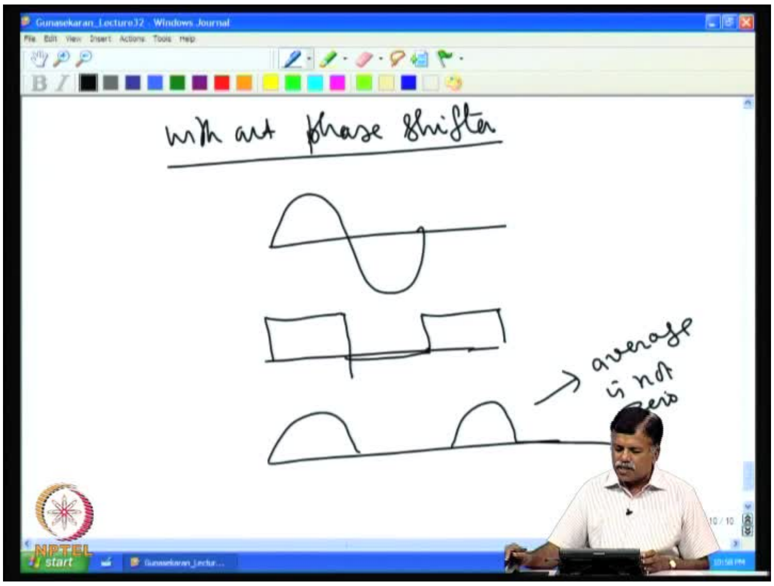

Suppose, if I make it without phase shift for example, if I without phase shift if I switched, then the signal would have been like this without phase shift. Without phase shifter, then the signal would have been like this and the square wave would have been like this, and the next wave would have been like this. Then, output after if it passed the switch then, you would have got the signal; the positive half cycle and the negative is not coming again the positive half cycle would have come. Average is not zero average is not zero that means, you would have got this signal.

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That means if I make it you know the switch, if I make the switch such that this and this are in phase. If these are in phase, then you will get maximum voltage. If this input voltage and the gate voltage are 90 degree phase shifted, then I will get a zero volt; average value as zero volt.

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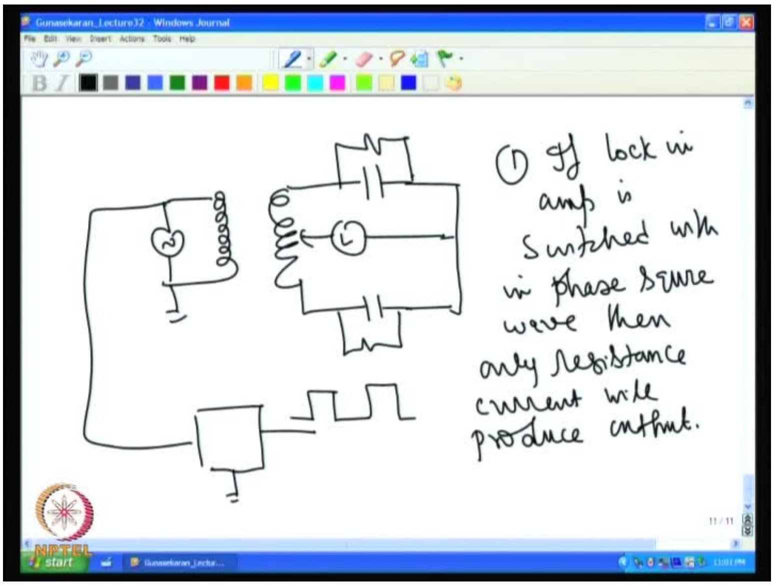

Now, using this one can separate out in phase and out of phase components, because if it is a capacitive component, then you would have got some phase shift. For example, in the lock in amplifier case, that we had both capacitance and resistance here. ((No audio from 28:25 to 28:34)) So, we have here lock in amplifier is used, now we connect this. Now lock in amplifier switches we have discussed. Suppose, if I make sure that, you know I take this is the input voltage I take this voltage, assume this is grounded I take this voltage and then, I square it up. I put a squarer, then I will get a signal which is square wave that is in phase with the applied voltage. This square wave is in phase with the applied voltage.

Now, if locks in amplifier switches are switched using this square wave that is in phase square wave. Now the lock in will be sensitive only for the resistive component, because the resistive component current will be flowing and lock in amplifier output, average output of the lock in amplifier will not be zero and then, you will have a resistive component. Now we know the capacitive current that is coming through this that is the capacitive current that is coming here is a 90 degree out of phase component, this current and this current both are opposite that this goes like this, and this current goes like this.

They are actually opposite but, these currents actually are 90 degree out of phase. But, we are switching that with in phase signal. So, the 90 degree out of phase current would have produced zero output. So, if I switch this for example, if the lock in amplifier is switched with in phase component in phase square wave in phase square wave, then only resistance current will produce output produce output.

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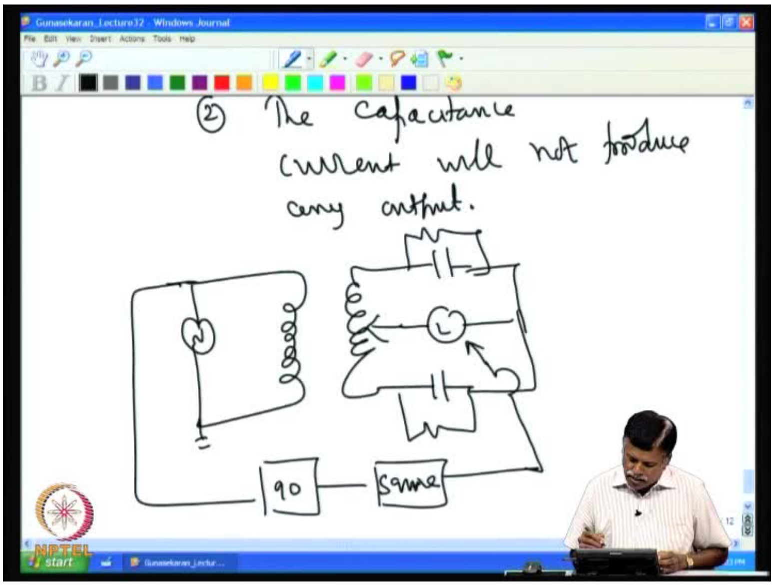

The capacitance 2, the capacitance current will not produce any output. Similarly, if I shift, I switch the phase shift, 90 degree phase shift and switch, then the capacitive component will be sensitive and resistive component will not be sensitive.

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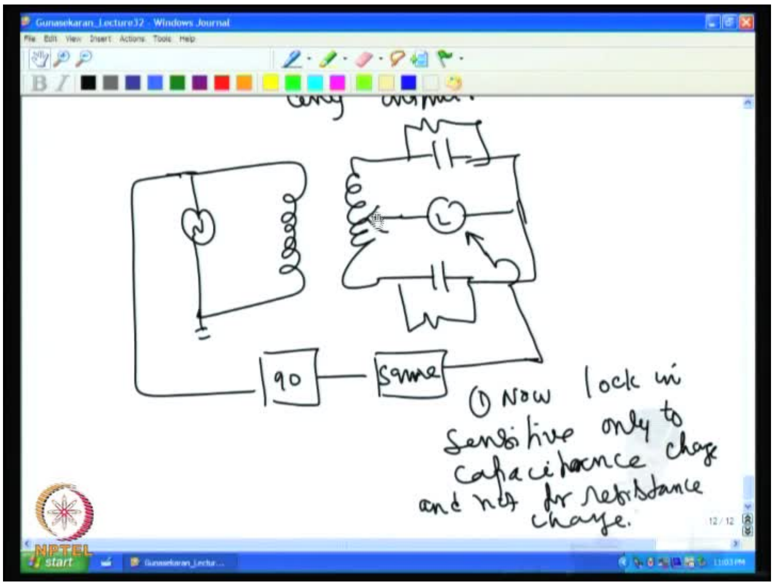

That is what we can do is that you have a lock in ratio transformer, now we have this resistance and capacitance. Now what to do is you take this signal and have a 90 degree phase shift, then I have a squarer, then I switch this to lock in amplifier I switch the lock in amplifier with this square, squarer. Now, if I do this, now resistance component will not be sensitive, only capacitive component will be sensitive. Now, lock in is sensitive only to capacitors, capacitance change and not for resistance change not for resistance change, because this is important. Because of this, one can separately balance out resistance and capacitance. That is making it first introduce a 90 degree phase shift introduce a 90 degree phase shift, and then it is sensitive for capacitance.

So, now I adjust this and balance the capacitance, then I remove the 90 degree phase shifter, then I balance it that balance is given for resistance. Of course, this works only when resistance value is very high. There are other issues involved when the resistance is not very high. When the resistance value is low, then you have other problems. So, as long as the resistance is high this works well. So, lock in amplifier that way can remove both the noise, remove the noise as well as it is capable of separating out in phase and out of phase component. So, let us see how to design the lock in amplifier? Thus now we are seen the theory that is behind the lock in amplifier.

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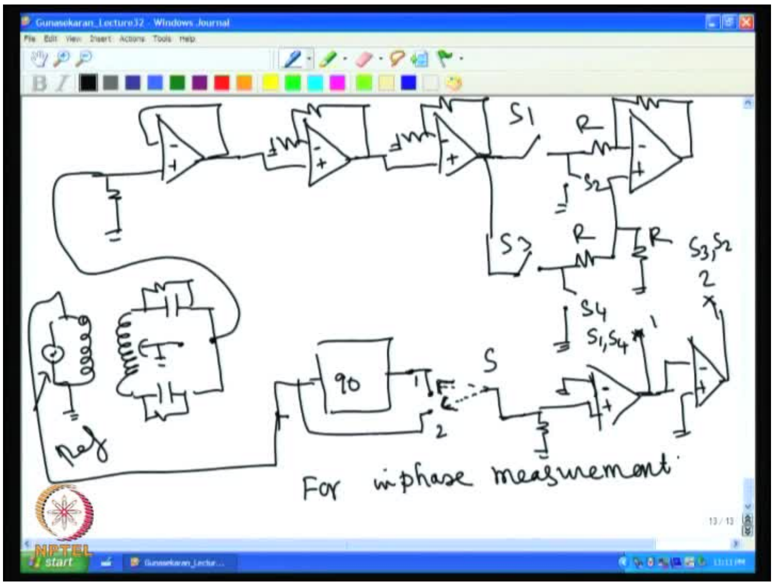

Now, let us see how to design the lock in amplifier? ((No audio from 33:49 to 34:04)) So, obviously we have sine wave as input excitation that is required. So, we take this capacitive measurement ratio transformer bridge only, example and they design the lock in. So, what to do is we will take the output of bridge that is output of the detector as an input to the lock in amplifier.

Obviously, the input signal we get this input is given here, then this conducts signal plus noise and also, we have sensitive to separate out the in phase and out of phase components. Then, I will have obviously amplifier so that, even the small signal is picked up, may be I need few stages of amplification. So, that not much phase shift is involved. So, you will have wide band bandwidth amplifiers, we amplify the signal.

Then, if you take the bridge here that the bridge consists of the primary and then, the two secondary's ((No audio from 35:25 to 35:35)) I think I draw it at this point, I draw it at the bottoms. So, will have ((No audio from 35:46 to 36:04)) essentially, this is the input to this and this is the excitation signal, and that is grounded. Now what I do is, I had to produce a phase shift and then the switching network. So, the switches can be lot we had earlier that will have the amplifier put here ((No audio from 36:25 to 36:53)). So, we have the switches…S 4.

Now, we have generate the signal which is actually, which is either in phase with the input or 90 degree out of phase with the input. That input signal is now this reference signal is our reference signal, now with respect to that we have to switch them. Assume there is no, assume phase shift introduced in this, in this and this. If that is the case, what can be done is that I can take this for example, if you want to measure the in phase component, then I can take this, then square it off. But then, I also want to have 90 degree phase shifter component. So, I can have a phase shifter here which is 90 degree phase shifter, phase shifter input, and then the output is here. Now what I do is, I can have a switch here which either selects in phase component or it selects one of them 90 degree out of phase component.

Then, this I will redraw this that I can select either in phase or out of phase component. Take this output, there is I have provision either to switch to this or switch to this, and then I take this output. This output is given to a squarer; the squarer can be a simple comparator.

So, whenever this is high for example, this can be used to switch on, when it is low it can be used to switch off. So, I can generate one more signal which is giving me another phase reverser. So, this I can give this and give to the ground. Now you have two square wave signals, both are 180 degree out of phase. You have square wave 1 and square wave 2 which are 180 degree out of phase. That can be used to switch these 4 switches for example, 1 can be given to s 1. If s 1 is on, we want at the same time S 4 also to be on, and the 2 can be given to S 3 when S 3 on, we want S 2 also should be on..

So, we can connect these to the gates of this that is the S, this output is given to the gate of S 1 and S 4, and this output can be given to gate of S 3 and S 2. If it is for example, if I want to measure in phase component if I want to measure in phase component, then I connect this switch. For example, this switch I call it as S, connect the switch S to position say I will put the position actually 1 here 2.

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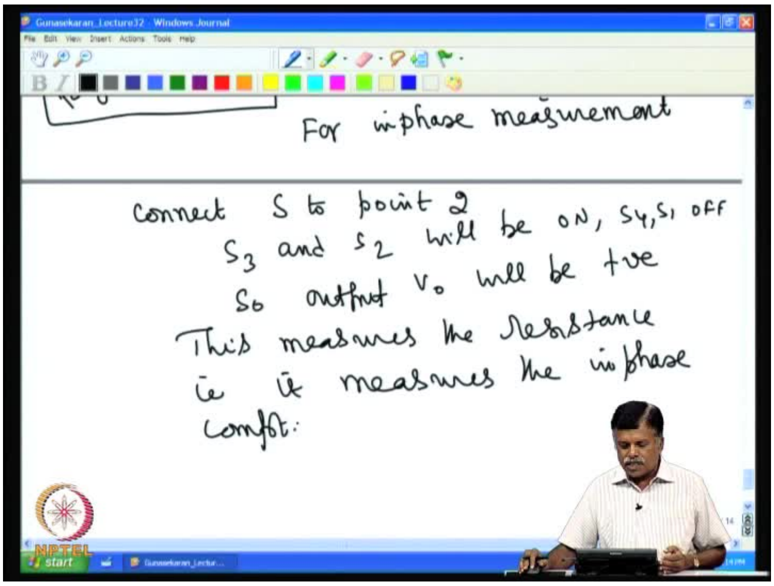

For in phase measurement, for in phase measurement connect S to point 2, now when it is in phase, you will have output here positive.

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So that will make this there is a small change here that I make this S 3. That is, if it is positive then S 3 to be on and then, S 2 should be on. So, when it is in phase component, when it comes in phase, then this will be high to the positive half cycle that will make S 3 on and S 2 on. And at the time this will be off so, you go to this one S 4 is connected to S 4 and S 1. So, at that time when say that is S 3 and S 2 will be on.

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For in phase measurement, then connect to point S 2 then, now S 3 and S 2 will be on S 3 and S 2 will be on that will produce a positive output. So, output V 0 so output V 0 will be positive and of course, here S 4 S 1 off that means, you will get in phase component now, because we have put at position 1 at point 2. So, you got in phase component and then switching is done for the incoming wave which is in phase. So, you got output which is positive half cycles and output is now sensitive for in phase component that is output is now sensitive for resistance measurement. Now for measure capacitance, this measures the resistance that is it measures in phase component. ((No audio from 43:45 to 43:54))

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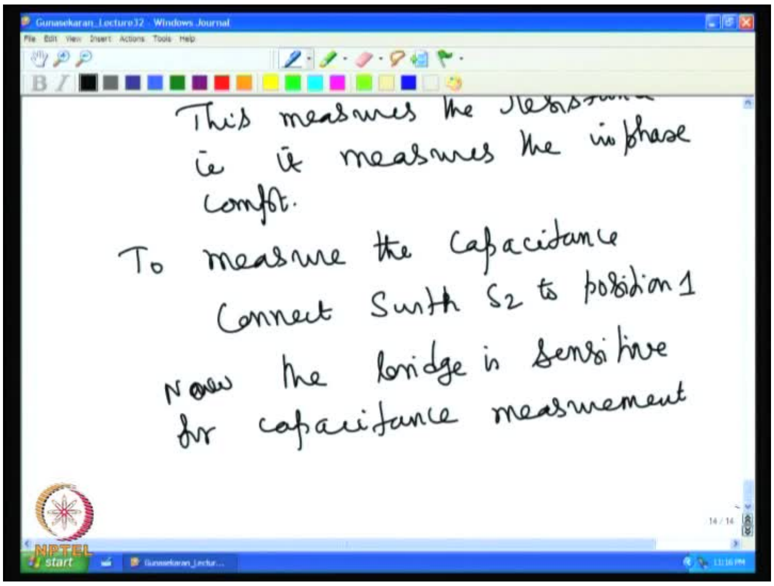

How to measure the capacitance? To measure the capacitance, connect switch S 2 position 1 connect switch S 2, switch S 2 to position 1. That is what we does that will now connect to position 1 here. So, the signal what you are getting here is 90 degree out of phase. So, the square wave is also 90 degree out of phase with respect to the input signal that is with respect to this. So, here whatever signal that is been switched, whatever that is switched will be 90 degree out of phase shift with respect to incoming wave.

So, the output now what you get? You will be 90 degree phase shifted or it will be in phase for capacitance current. Now it will be sensitive for capacitance current. Now, the bridge is sensitive for capacitance, bridge is sensitive for capacitance ((No audio from 45:22 to 45:36)). So, the output of the lock in amplifier will be, will give only the capacitance component. And we will have that is if it is averaged only capacitance component and also it will be removed of the noise.

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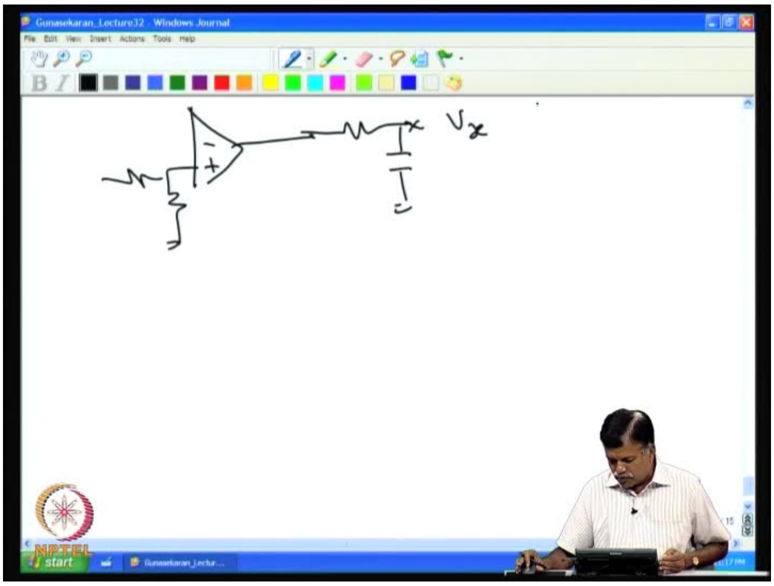

If you look at the output now, we filter it from the output of the switching stage that you will get this output. So, V x will be without noise and also output can be selected for in phase and out of phase. Now this is the very important instrument as for as signal processing is concerned. Particularly, the signal is buried in noise, one can remove the noise and as well as, we can separate out in phase and out of phase component using the lock in amplifier.

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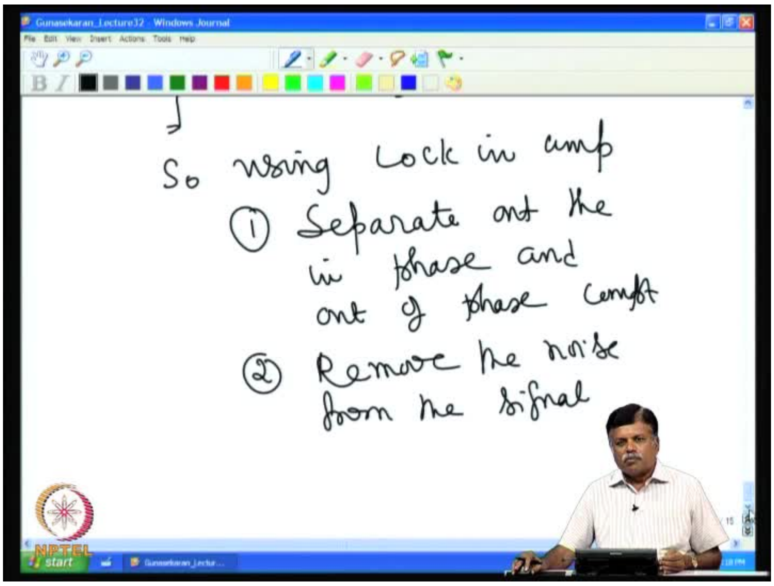

So, using lock in amplifier, the two things can be done. 1, separate out the in phase and out of phase component separate out the in phase and out of phase component ((No audio from 46:52 to 47:03)) 2, remove the noise remove the noise from the signal.

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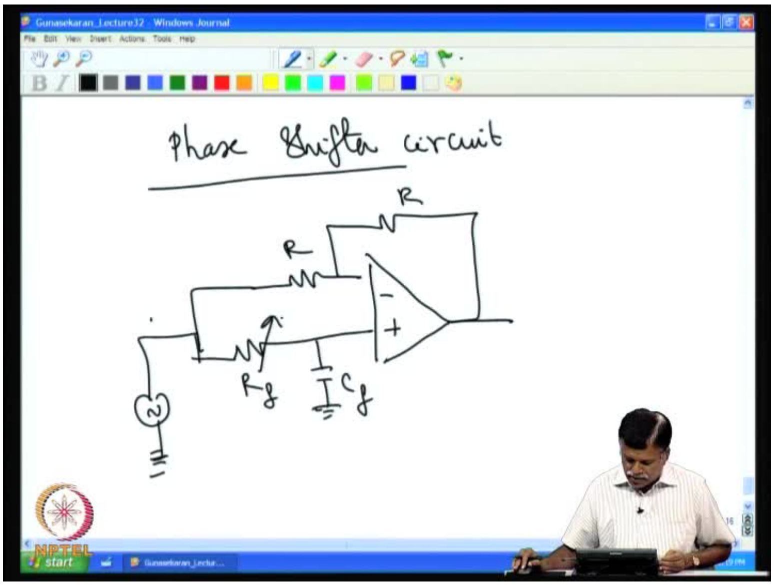

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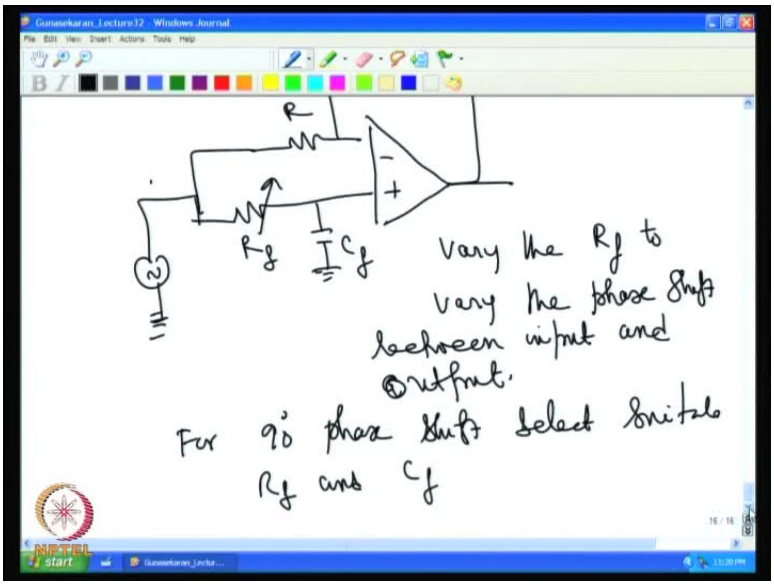

That is why the earlier days lock in was very popular, even today lock in amplifier is very popular but, this also can be done digitally. For example, before discussing the other use of the lock in amplifier, I just give you the circuit diagram of the phase shifter.

So, that one can willing to one can design the full lock in amplifier actually so, for example, the phase shifter circuit can be like this, phase shifter circuit. The input ((No audio from 47:56 to 48:11)) like then only equal resistance are put compare to R filter and C filter. By varying either R f or C f, one can vary the phase shift vary the R f to produce to vary the phase shift vary the phase shift between input and output. ((No audio from 48:42 to 48:52))

Now, this phase shift this can give maximum of 180 degree phase shift. So, one can set whatever phase shift required in this stage for example, you can select for 90 degree phase shift, the resistance can be selected and the capacitive component. So that, 90 degree phase shift appears at the output. So, for 90 degree phase shift for 90 degree phase shift, select suitable R f and C f. The phase shift of course, depends upon the frequency. And if more than 180 degree phase shift required, the two stages can be added together.

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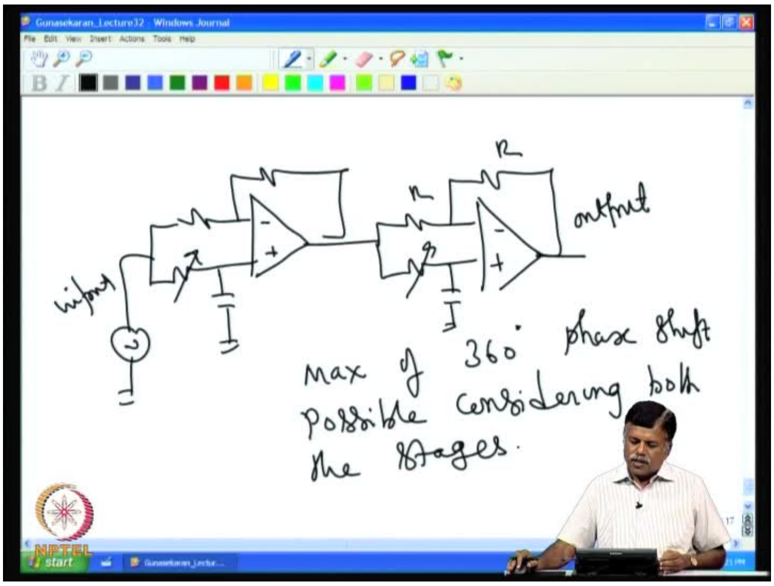

So, one can have normally two stages of phase shift. For example, you can have ((No audio from 49:52 to 50:07)) which actually can give you maximum of 360 degree phase shift considering both the stages. So, one can get if between the input and output, input and then the output you can have 180 degree phase is possible. Maximum of 360 degree phase shift possible, considering both the stages, each stage gives 180 degree out of phase.

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So, considering both the stages so, normally we need to have an additional phase shift other than the 90 degree phase shift that what we had shown here. We are shown only 90 degree phase shifter and addition to this 90 degree phase shifter, we yet have additional phase shifter required to compensate the phase shifted occurred in this stages. Because in actual case, phase shift here there will be some phase shift here and there will be some phase shift here.

And simply by shifting 90 degree exactly, we are not able to switch in phase and out of phase. So, natural lock in amplifier, we need to reduce additional phase shifter here in this stage. So that, one can have this phase shift will be equal to this. So that, one able to get in phase and out of phase component accurately.

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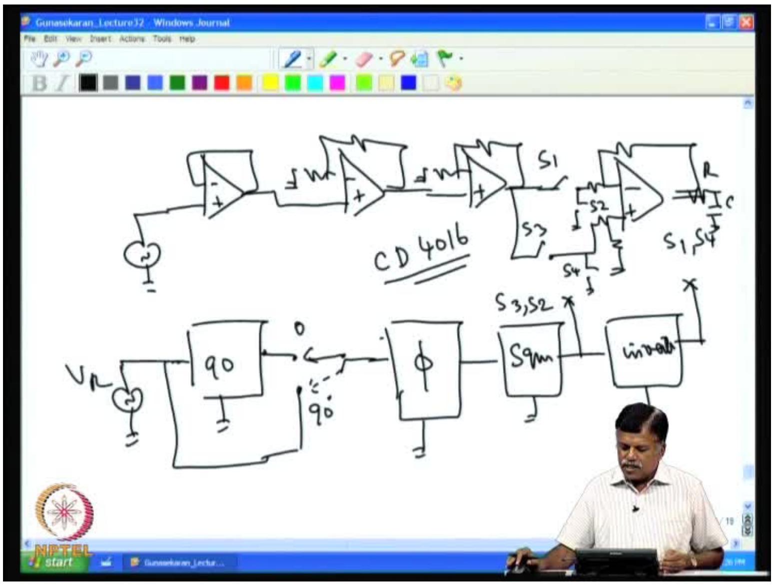

So, if you look at the total lock in amplifier, it looks like this that you have series of amplifier set the input. You know we have a voltage follower and then the amplifier stages, then you will have this switches which we had seen earlier then you had this. So, you have the plus minus the switches, then this input signal whatever was coming that reference signal was the same reference signal was taken. Reference voltage and that actually you will have a 90 degree phase shifter 90 degree phase shifter with a provision for selecting in phase and out of phase component.

Then, this might need additional phase shifter additional phase shifter and then, the squarer, then inverter that this inverted output is for two switches and this is for two switches. So, you have S 1, S 2, S 3 and then, you have one more switch here S 4.

So, this is supposed to be given to S 1 means, then S 1 is on that it also has go to S 4, and then this has go to S 3 and S 2. So, one can select in phase and out of phase component by one can say this is 0 and 90 degree 0 and 90 degree. So, one if you want to measure in phase component, then select the 0 degree position and then introduce a phase shift, the phase shift will be equal to phase shift introduced by these amplifiers. So, you got at this point, see this sine wave which is in phase with the signal here. Now you square it up to make it as square wave. So, the switches are switch and then, to produce the reverse square wave then invert it and then again get as square wave. And these outputs can be connected to these switches.

Now that completes the lock in amplifier design, because I had already given you, how the phase shifter to be made and how the squarer and inverter to be made. Only thing is these switches are not discussed in detail. These switches are analog switches which are available for example, the typical switches C D 4016 which is an analog bilateral switch which allows both positive and negative analog voltage to pass through. So, one can configure this using a plus minus power supply. So that, these switches also can be working properly so, for use analog switches for C D 46 that will make the lock in amplifier complete.

And then of course, the output should be connected through a time constant, this R C. The time constant must be selected larger that time constant betters the noise rejection. So, one can have varies of R C and if necessary this output also can be taken out using a voltage follower circuit. Now this lock in amplifier of course, we are getting a output voltage which is not sensitive to noise in the sense, noise signal which is buried in the noise can be extracted. Of course, the output voltage is only DC; the original signal is not retained as it is. Of course, we able to supply to in phase and out of phase component and we able to remove the noise but, the original sine wave is loss the output, we do not get the original sine wave.

There is another device called boxer integrator which was earlier day's use which can be even give back the original signal wave shape. So, that issue we will discuss in the next class before getting into other issue of A C amplifier. Thank you.