Analog Electronic Circuits
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Lecture – 24
Circuits with op-amps

Welcome, back to Analog Electronics. This is lecture – 24. Today, we are going to talk about circuits which are using op-amps. So, in the last class we had started discussing op-amps basic circuits, adders, subtractors, right. So, the idea was always to use superposition whenever there are more than one input.

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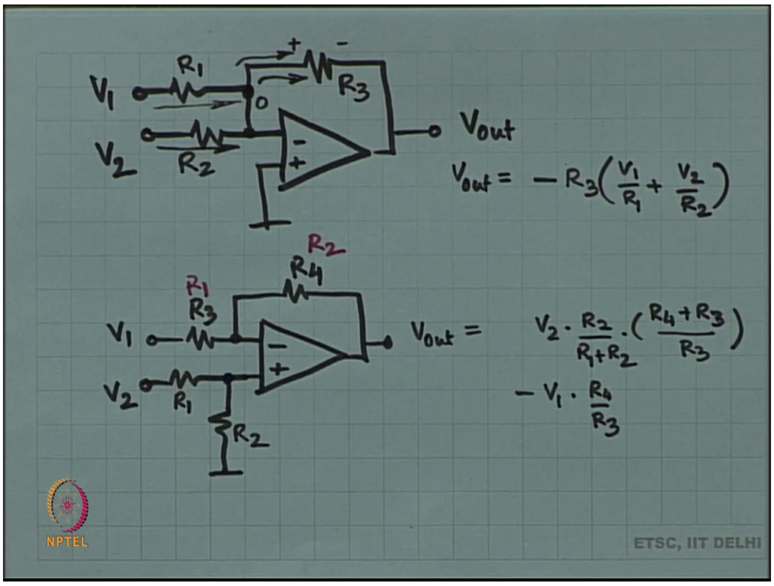

So, the adder circuit was right. So, you add two currents and then push it through a feedback resistor. So, this was basically the idea. So, I 1 is V 1 by R 1 and that has nowhere to go, but through R 3 and likewise I 2 is V 2 by R 2 and that has nowhere to go, but through R 3. There is no alternative, and the current going through R 3 is the sum of V 1 by R 1 plus V 2 by R 2 and therefore, the drop across R 3 is R 3 times V 1 by R 1 plus V 2 by R 2, this is the drop across R 3 and it starts from a potential of 0. So, it ends at a negative potential of minus R 3 times V 1 by R 1 plus V 2 by R 2.

So, this is basically the idea in this case, alright. So, this was the adder. So, the reason why we called this an adder is because the currents got added, ok. Otherwise this is pretty much the operation you get an addition and also an inversion the other one which is the subtractor is using the two different terminals of the op-amp, ok. So, in this case you apply super position again. So, that voltage at the plus terminal is V 2 times R 2 by R 1 plus R 2 because it is potential divider. This voltage is going to be amplified by a factor 1 plus R 4 by R 3, ok. So, you have got if I apply only V 2 and V 1 is ground then to start with the voltage at the positive terminal is V 2 into R 2 by R 1 plus R 2. This voltage is going to be amplified by a factor remember V 1 is ground this node is at ground, this node is V 2 times R 2 by R 1 plus R 2.

So, you get the non inverting amplifier configuration and therefore, the voltage at the output V out is the voltage at the plus terminal times 1 plus R 4 by R 3, ok. So, this is the gain from V 2 the output and likewise there is a gain going from V 1 to the output when you do V 1 to the output V 2 is going to be at ground, but then potential division will ensure that the term voltage at the plus terminal is also 0 volts, right.

So, with V 1 it is just minus R 4 by R 3. So, this is the overall idea. Now, if you want if you want these factors to be equal and you can engineer them to be equal all you have to do is what do you have to do if you want to make sure that they are equal you just make R 4 plus R 3 equal to R 1 plus R 2. So, these two cancel out and this therefore, becomes. So, make R 4 equal to R 2 make R 1 equal to R 3, alright. If I make R 4 equal to R 2 and R 1 equal to R 3 then what is going to happen R 4 plus R 3 is the same as R 1 plus R 2.

So, these two will cancel out R 3 is the same as R 1. So, this is V 2 times R 2 by R 1 R 4 by R 3 is R 2 by R 1. So, overall you get R 2 by R 1 times V 2 minus V 1, ok. Anyway, this is just playing with values you can figure out you can instead of doing just an addition or just a subtraction you can do weighted addition, weighted subtraction by utilizing the values of R 1, R 2, R 3, R 4, ok. So, this is just addition and subtraction operations.

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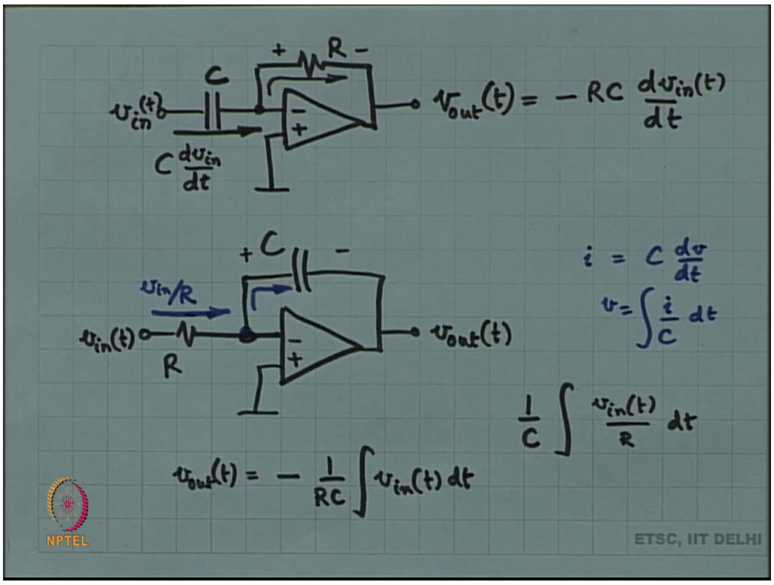

The op-amp can also be used to do other more interesting operations, for example, integration and differentiation. So, if this were to be a resistor and the minus terminal is at ground then this current is going to if it was R then the current could be input divided by R right, but now that this I have placed a capacitor over there, if I have input voltage v in of t then what is the current if this is C C dv by dt. So, C dv in of t by dt. So, this current goes in it has nowhere to go, but to go through R and therefore, it creates a potential drop across R right and therefore, the output voltage v out of t is equal to minus R C times dv in dt, ok.

So, this is called a differentiating circuit differentiator and likewise you can make an integrator what is going to happen here if this node is at 0 then the current coming in then the current coming in is nothing, but v in by R and this current is forced to go through the capacitor it has no other way to go and therefore, if I know the current going into capacitor the voltage developed across the capacitor is proportional to the integral of the current right C dv by dt is the current. So, the voltage is integral of so, i is C dv by dt for a capacitor.

So, voltage is integral i by C, correct for capacitor. So, in this case I know the current the current is v in by R. Therefore, the voltage drop across the capacitor is 1 by C times integral v in of t by R dt that is the voltage drop across the capacitor or in other words v out. So, is the voltage drops.

So, V out is so, is at the minus terminal. So, V out of t is equal to minus 1 by RC integral v in t dt. So, this is the way it works now there is a problem with the integral this integral is definite or indefinite basically you start a time t equal to minus infinity and you keep integrate right. And since, we do not know the history of the circuit it is not very clear how to do the job, alright. So, you can do it this way you can keep an indefinite integral and then you can add constant to it, right an arbitrary constant which indicates the starting point. Now, in variably what happens is that this arbitrary constant is going to be such that the circuit is no longer go into work, ok.

So, this circuit does not really work like this the integrator does not work. The reason why it does not work is because there is an arbitrary constant and this arbitrary constant can be anything it can even be equal to V dd e or it can even be equal to the minus supply or whatever you want right and as a result the circuit is going to clamp to the power supply and the op-amp is not going to work. There is one more way of seeing this if you look at this particular circuits then at DC, when you try to work out the DC operating point at DC this capacitor is an open circuit, ok.

It does not exist at DC which means that there is no feedback around the op-amp and therefore, you remember in the last class we had those curves you know we had the KCl curve and then we had the op-amp curve and then we had the point of intersection all of that does not really apply anymore because this KCl does not really workout for you this capacitor is not there, ok.

So, all these currents are 0. So that KCl curve is no longer there. So, you can be anywhere on the op-amp curve, whenever you can be anywhere on the op-amp curve right Murphy you know Murphy is loss. So, Murphy is as that if something can go wrong it certainly going to go around ok. So, this is one of those situations where Murphy is going to take over charge right Murphy is going to declare that this op-amp is not supposed to work it is not going to work at all.

So, the reason why did not work is the absence of negative feedback at DC. So, if someone asks you what is the reason why did this op-amp not work, right? Why does this circuits not work? In that case you will have to give the answer that this circuit does not have negative feedback at DC. If you give this answer it is a complete answer. Otherwise you will have to draw all kinds of curves you will have to show that there is no KCl going on over here you draw the op-amp curve it is still you know beating around the bush, right, you can say that there is constant of integration you are still beating around the bush,.

The correct precise answer why does this circuit not work, the circuits does not work because there is no negative feedback at DC and therefore, the DC operating point of the op-amp is not established, ok. You want a nice clean operating point such that the op-amp has high gain, and that does not get established when you have this kind of a circuit.

So, this integrator is nice in theory, but it does not to work. However, we are smart, we make it work, right. We make it work in scenario where this integrator is part of subsystem and overall there is DC negative feedback to establish the operating point from outside; So, a higher circuit.

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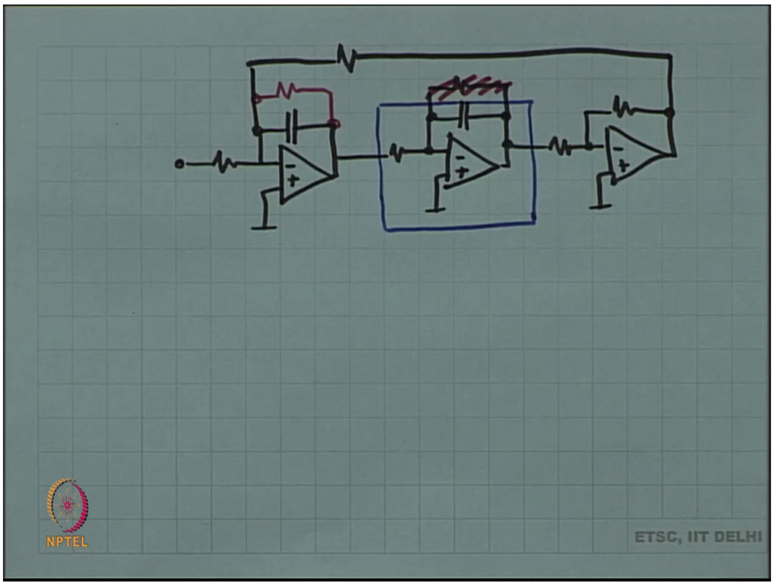

So, at this level of abstraction the circuit does not work , but if I use this circuit as part of a bigger block let us say in a circuit that looks like this. So, this is one integrator, this is another integrator, ok. Let us say this is not just any integrator it is gives some damping to it, something like this ok.

So, you got an integrator which is part of bigger system or you could even have this, ok. You can be you can construct many different scenarios. So, this is an integrator by itself this circuit by itself is an integrator standalone it is not going to work, but when it is part of this bigger circuit it is going to work. Why is it going to work because hopefully there is negative feedback at DC and that is going to established the DC operating point. So, let us see let us do an example.

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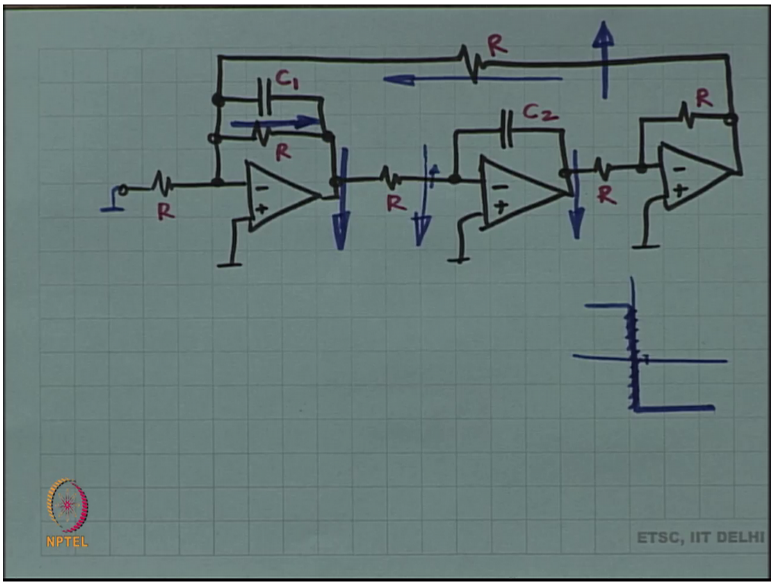

Let us take this particular circuit as an example, alright. So, let us take this as an example, let us say all the resistors have value R and let us say the capacitor the first one is C 1 the next one is C 2 all resistors have value R, alright this is the circuits. Now, what happens over here how do I see how do I check that this particular op-amp has negative feedback at DC I need to check that.

So, suppose the voltage at this node is slightly high slightly higher than the requisite voltage to give it high gain, right. It the op-amp should be in this region. Remember, in the previous discussion we discussed the op-amp has to be in this high gain region right; the other two regions are flat there is no gain the op-amp has to be in the high gain region. So, the operating point of the op-amp the that input voltage of the op-amp has to be such that you are in this region, ok.

So, let us say you are not you are slightly higher you are slightly higher over here you are somewhere over here in which case what does this mean what is the output of the op-amp it is the lower power supply right you are slightly higher than required. So, therefore, this is very low, fine. You have got an R another R, so, therefore, what is the output over here just the opposite, right it is gain of minus 1. So, the voltage here is equal and opposite, fine. Now, that is getting fed back to the first op-amp. So, the input to the first op-amp one of the two inputs to the first op-amp has a very high voltage, right which means lots of current is going to come in if lots of current comes in then what is going to happen all that current is going to go through this resistor remember C 1 is open circuit at DC's. So, it does not matter we are talking about DC only C 1 is not there at DC. So, all of that extra current because this is high voltage is going to come through this resistor R lot of current all of that current is going to flow through this R right over here.

Why this R, why not the other R because the other R is right now this side is also at ground we are thinking superposition, ok. So, you think superposition this side is at ground this node is at ground. So, this cannot carry any current ok. So, all of that current is going through this R which means that the voltage here is going to be exactly the same negative, ok.

So, slight increase in voltage caused a drop in voltage over here and this there is no current in this branch. So, the voltage over here is the same as is going to pull this particular node back down, ok. So, that is negative feedback for you. You create a slide disturbance slide positive disturbance force comes back and pulls you down, ok. If you had a slight negative disturbance at the same spot then the force would come back and push it up, alright.

So, that is DC negative feedback with the help of DC negative feedback the operating point of this op-amp is established and therefore, the integrator is going to work under these circumstances in side this bigger circuit, ok. It is not going to work stand alone it is going to work as part of bigger circuits. Now, just as an interesting exercise can we analyze this particular circuit it is very interesting circuit it is actually very famous circuit I am going to tell you the name of the circuit after we analyze it, ok. So, let us first analyze the circuit. I am going to draw it for your benefit yet again.

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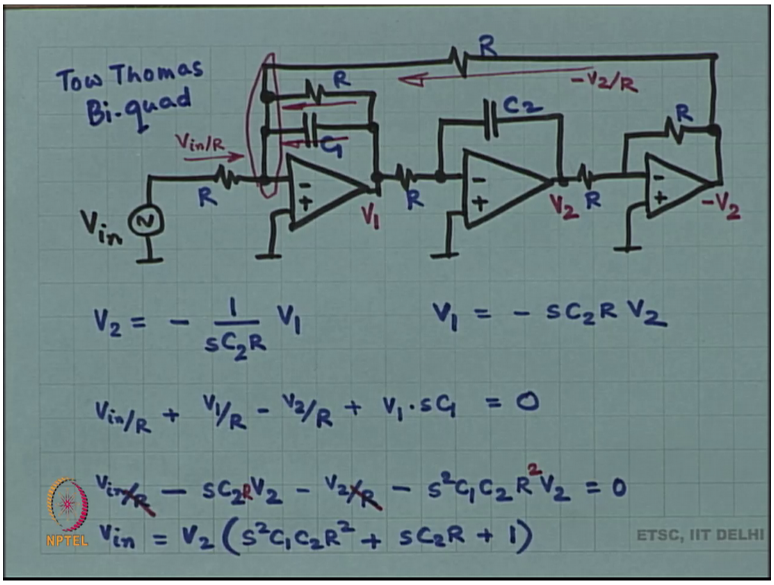

Ok, of course, you can have different values of R they do not necessarily have to be all equal, but without any loss of generality, just so that my analysis is easy right I want to reach some answer quickly. So, therefore, I have placed everything as equal. However, in a certain situation you might want these resistor values to be different there is no reason for them to be equal no other reason for them to be equal only reason why they are equal is so that my analysis is easy, right. Now, in front of you very bad reason, but that is what it is, right.

Now, we have already established that all the op-amps have DC negative feedback by the way this op-amp also the first op-amp has DC negative feedback because you have got an R, ok. The third op-amp also has obviously, as DC negative feedback you do not have to worry about it, ok. Now, let us see let us call this voltage V 1, V 2 and if this is V 2 what is the output. The output is obviously, minus V 2 because this is R and R this is an inverting amplifier. There is a relationship between V 1 and V 2, V 1 by R is the current coming in over here that current goes through C 2 and therefore, V 2 is equal to minus 1 by SC 2 R V 1, that is the integrator relationship, fine.

Now, the current here is V in by R the current this way is minus V 2 by R, alright and the current through the capacitor C 1 is V 1 times s C 1 the current through this R is V 1 by R and if you do KCl at this node, ok, what do you get you get V in by R plus V 1 by R minus V 2 by R plus V 1 times S C 1 is equal to 0, fine. I did it this way because there were many branches over there, ok. I it was not really straightforward what else could be done, fine. So, my assumption is that this node is at 0 volts which is more or less correct because the op-amp is in it is high gain region because of DC negative feedback and then with that assumption in mind this current is minus V 2 by R this is V 1, V in by R this current is V 1 by R this current is V 1 times SC 1 and the sum of all of these currents is equal to 0 KCl.

And, over here we already know V 2 relationship between V 2 and V 1. So, let us say that V 2 is my desired output quantity if I take if I think that V 2 is my output of the circuit or minus V 2 is the out of the circuit then will we are going to replace all the V one's in the equations with V 2. So, let us replace. So, V 1 is minus SC 2 R times V 2, right and let us replace all the V one's with V two's.

So, I have V in by R minus SC 2 R R cancels out V 2 minus V 2 by R minus S squared C 1 C 2 R V 2, and something very convenient over here would be to multiply the entire equation by factor R, ok. So, if I multiply the whole thing by R this is what I get first term becomes V in the second term becomes S C 2 R times V 2 why did I do that. So, that all the terms have dimensions of voltage.

So, the first term is voltage the second term is s which is one by time time C 2 R which is time. So, one by time times times times time is nothing times V 2. So, the second term is voltage third term is V 2. So, it is voltage fourth term is S squared which is times 1 by times squared time C 1 R which is time C 2 R which is time, ok. So, the second term is also just voltage. So, all the terms R now in terms of voltages, and next what do you do you compile all the V 2 together. So, V in is equal to V 2 into S squared C 1 C 2 R squared plus S C 2 R plus 1, alright.

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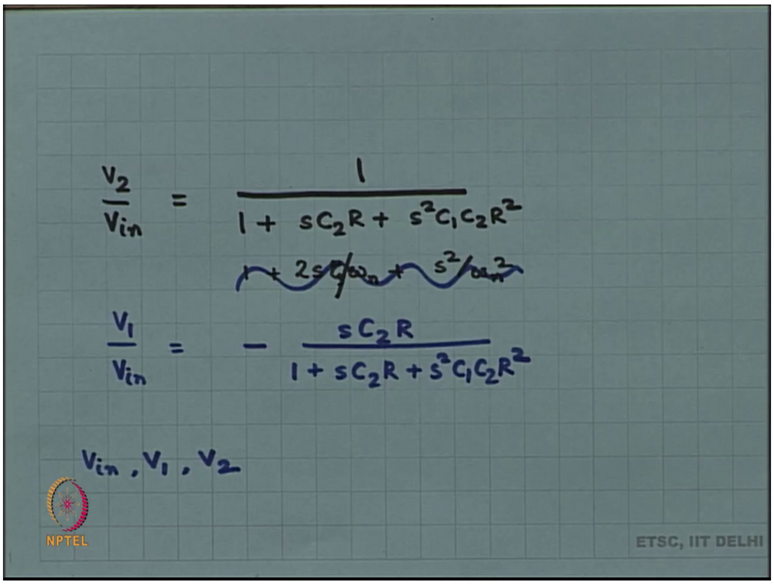

Or, in other words you have created V 2 by V in is equal to 1 by 1 plus SC 2 R plus S squared C 1 C 2 R square, and this pretty much means that you can create an arbitrary second order low pass transfer function, right. You have got full control over the value of C 2 R right just have to choose the right time constant and then if I know C 2 R you have full control over the value of the second term also you can choose any value that you want. So, you know like all you have to do is choose the right C 1 times R, ok.

Remember the denominator looks sum what like this right 1 plus S 2 times S what was it zeta omega n something like this, ok. It does not really matter, ok. So, you got two control objectives one is zeta the other is omega n and you can fix them with the help of the two time constant C 2 R and C 1 R, alright. And in any case as I said before R I have chosen all the values to be equal to R need not be the case, you can mix and match right, ok.

So, this gives you an arbitrary low pass transfer function now remember V 1 is nothing, but SC 2 R minus SC 2 R times V 2. So, if you pick V 2 if you if you pick V 1 as your output then you pretty much get. So, you get something else in the numerator, right. The nominator remains the same you get something in the numerator. So, this is if you look at it carefully this is band pass transfer function, and with the help of V in V 1 and V 2 you can arbitrarily add V in V 1 and V 2 and weight and add you can create any second order numerator polynomial as well as any arbitrary second order denominator polynomial. All you have to do is weight the coefficients right you already know how to make adders and subtractors, right and then add and subtract appropriately. So, one more op-amp add and subtract appropriately and you can create any arbitrary second order numerator by any arbitrary second order denominators alright. So, this particular circuit is called bi quad in short form bi quadratic circuit it is named after the first person who made it is called the Tow-Thomas, Bi-quadratic.

And, it is a fantastic circuit because you can create any arbitrary second order transfer function with the help of this circuit with the possible addition of one extra op-amp. So, three op-amps plus one more and that is it you can create any arbitrary second order transfer function numerator by the nominator, alright. This is something that is used by a lot of people to make filters to design filters, low pass filters, high pass filters, band pass filters, right band stop you can make anything as I said all filters can be designed with the help of this.

So, lot of people fall back on this lot of people what they do is when they see that they need to make complicated filter transfer function, some numerator divided by some denominator then they break up the denominator into pieces which are second order and first order, right. It is always possible to factorize figure out where are the poles of the denominator.

So, the denominator will have some complex conjugate poles and some real poles right. So, you take the complex conjugate poles those are second order sections, ok. You take the real poles those can be treated as first order sections or you can combine them two of them to get one more second order section, right and then you arrange the denominator as many second order sections and maybe a first order section, right. And then you make that many number of bi-quad circuits each bi-quad circuit trying to representing one of those second order sections, right. The first order section does not really need much discussion it is just one of these the first just the first one will give you first order section.

So, you do not really have to work very hard for first order section ok, but the second order sections might need work and this is how you make the second order sections. You just cascade all of these second order section and make any arbitrary filter transfer function or any arbitrary transfer function you have h of s some numerator, some denominator, factorize numerator factorize denominator collect all the poles right smartly to smartly collect the poles, if you are unsmart about it bad things will happen, right.

So you smartly collect all the poles, smartly collect all the 0's right pair of poles by pair of 0's, one Tow-Thomas bi quad. Another pair of poles by pair of 0's and other Tow-Thomas bi quad right and in two or three sections, three sections will give you sixth order numerator by sixth order denominator. Invariably for low pass filters the numerator is not even required, numerator is 1 for a lot of low pass filter for lot of not all lot of low pass filters numerator is just, in which case nothing much is required with the numerator.

Some if you try to be smart with low pass filter then the numerator would not be 1 anymore, right there might be 0's in the numerator polynomial, if you try to place 0's in the numerator then you know you will have to work with the numerator polynomial as well. But you understand how to work with the numerator polynomial all you have to do is add weight and add V in V 1 and V 2, that will get you the 0's otherwise standard low pass ones; especially if you try to make butter worth and Chebyshev responses or even Bessel filters, Butterworth filters, Chebyshev filters those are all pole there are no zeros in those. So, you do not bother about zeros you just make it with the Tow-Thomas bi quad multiple sections.

So, you might have studied other strategies in circuit theory in circuit theory you would have studied strategies where you build the circuit with the help of a ladder with inductors capacitors sometimes even mutual inductances, right. You can do it with op-amps right and with op-amps this it is not very big struggle, all you need to know if what is the numerator what is the denominator factorize using MATLAB or any other program you know the exact locations of the poles exact locations of the 0's. And then you smartly collect them and that is it, right. It all falls in place, there is no you do not have to iterate too much, alright.

Now of course, this is all fine, but the technique that you learnt in circuit theory is actually the better one. This is this is fine, this will work out to some extent, but whenever you try to make complicated polynomials, right higher order systems anything more than third order if you try to make implement anything more than third order things are not really going to work out very smoothly. If you try to do it with the Tow-Thomas bi quad, but otherwise the Tow-Thomas bi quad is a very nice approach because cleanly you get the whole system in one shot.

Let us discuss some more op-amp circuits. So, this is a fantastic op-amp circuit which is used all the time a lot of people like making filters with the help of the Tow-Thomas bi quad because it is so easy to make just by the way this is out of context, but filter design is actually a nice subject and not a lot of people know how to design filters. So, those who do not really know how to design filters, right, invariably for them a shortcut is the Tow-Thomas bi quad break up in second order, first order polynomial it is easy to understand and then implement using Tow-Thomas. Now, those who are no filter design they will tell you that do not do it that way do full ladder network because that will give you far better performance, ok.

And, then the ladder network can also be transformed into a circuit that uses op-amps we would not do that right now what I would rather do is another second order circuit that is an extension of this one.

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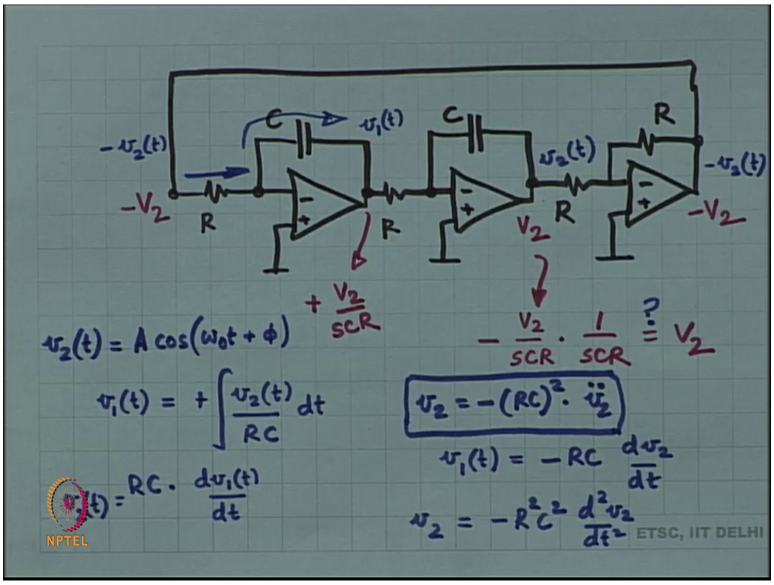

So, by the way this Tow-Thomas bi quad I have drawn it three times today already, but is there I mean am I drawing it out of memory have I memorized it the circuit or did I am I constructing it. So, it turns out that it is very easy, very straight forward to memorize the circuit you do not have to be does not take much. The first stage is a damped integrator, the second stage is a pure integrator the second stage is an integrator the first stage is a damped integrator an extra R. So, damped integrator, integrator the third stage is nothing much it is minus one feedback, ok. It is very easy to memorize damped integrator, integrator, feed minus 1 feedback.

So, the circuit I am going to draw now is going to be an integrator another integrator minus 1. So, instead of damped I made it pure integrator and then I am going to apply feedback and in this case I am not going to bother with the input the input is the feedback. So, without any loss of generality I am going to assume all the resistors are equal and let us also assume all the capacitors are equal without any loss of generality. In the earlier case if I assumed that the capacitors very equal I would lose generality because I would not have been able to synthesize the two denominator coefficients, you had one and then you had one more coefficients and one more right.

So, those two coefficients I would not have been able to synthesize because I would not have enough degrees of freedom, right. In this circuit let us just make it all equal, all R's are equal, all C's are equal forget about the degrees of freedom; So, only one degree of freedom, fine. Now, you are going to say what kind of circuit is this it does not have an input and yeah, I agree it is very funny very strange circuit which does not have an input. Let us just think about it for a little bit, let us let us assume this voltage is V 2 like before.

So, the voltage out here is going to be minus V 2 because this is just minus 1. So, minus V 2 over here and therefore, the voltage at the output of the first integrator is going to be minus 1 by SCR times minus V 2. So, this is going to be minus 1 by SCR which is the integrator times V 2. So, it is going to be plus V 2 by SCR, and then V 2 by SCR is being integrated and you are getting V 2 back.

So, if you integrate V 2 by SCR what do you get V 2 by SCR into minus 1 by SCR, and that happens to be equal to V 2 this is very straight, right, it is not really looking nice; Is not looking nice at all, alright. Let us look at it in the time domain when things do not work out in the frequency is domains lot of times might be nicer to move to the time domain where things are a little more tractable, ok, let us think. This is v 2 of minus v 2 of t, this is minus v 2 of t, this is v 2 of t, and this was v 1 of t which is fine. I will I just try it out what is happening.

So, I have got minus v 2 of t that goes through R right and that is pushed through the capacitor. So, the voltage this is v 1 of t, v 1 of t is nothing, but minus v 2 of t by RC integral dt, ok, minus of that, alright. Now lot of times you do not feel nice with these definite integrals. So, you can write it in a slightly different way, you could write it as the differential of v 1, right. So, if I do RC times dv 1 t dt then that will be v 2 fine. So, I am saying is the instead of saying is v 1 is the integral of v 2 let us say minus v 2 is the differential of v 1, ok.

So, minus v 2 is the differential of v 1, let us look at it backwards and likewise v 1 is the differential of v 2, ok. So, v 1 of t is nothing, but minus RC dv 2 dt and then v 2 is RC dv 1 dt which. What does it mean? It means v 2 is nothing, but minus R squared C squared d squared v 2 by dt square or in other words you have magically arrived at the harmonic oscillator equation right this is the oscillator equation, right v 2 is some minus something times v 2 double dot.

And, what does this mean this means that this circuit is going to oscillate at what frequency? At frequency of 1 by RC so, omega naught is going to be 1 by RC omega the angular frequency is going to be 1 by RC, fine. So, in other words V 2 of t is going to be something some amplitude unknown amplitude times cos omega naught t plus some unknown phase where omega naught is nothing, but 1 by RC. Any questions so far? So, this particular circuit it is it is an oscillator it is one of the few oscillator circuit that actually gives you pure sine wave, ok. The reason why it gives you a sine wave is because it oscillator at this frequency and only at this frequency it does not oscillate at any other frequency. So, no harmonics it give you nice clean sine wave.

So, for example, if you want to synthesize the sound of a flute sound of a flute is a pure sine wave if you played nicely other most other instruments can have harmonics usually they have a lot of harmonic content, other instruments. A flute can be made to sound like pure sine wave, right and if you want to synthesize the sound of a flute this is the way to do it, ok.

This is one of the few circuits that can actually synthesize the sound of flute otherwise you will have to do a lot of other complicated you will have to have d s p, a to d converter d sorry d to a converter right. We have to generate the codes in the digital form and then two digital to analogue conversion that also will create harmonics and so on and so forth, then filtering and so on so sine wave oscillator this is one of the few sine wave oscillators, alright.

Most of our other oscillators are non sine wave. They start generating square waves, triangular waves, all kinds of other things, right. This is one that gives you sine wave this called the double integrator oscillator. The reason why it is called double integrator is because the first stage is an integrated, the second stage is another integrate, third is just minus 1, right you need the minus 1 to create the negative DC feedback, alright. The negative DC feedback is going to make sure that this op-amp is under control, it is minus terminal, if it increase slightly this gone to be overall feedback and it is going to decrease second one is also going to be under control with the help of DC negative feedback,.

So, let us stop here. In the next class we are going to switch little gear and we are going to to change gears little bit and we are going to start discussing other things, ok.

Thank you.