Introduction To Electronic Circuits
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Module No 01
Lecture 23: General Network Analysis

This is the 23rd lecture on general network analysis and this I had commented earlier, shall mark the conclusion of the part on circuits of this course. And today's and tomorrow's lecture, we shall concentrate on this and then the 3rd lecture from today shall be on electronic circuits. So far, we have only considered very simple networks in which levels are connected in series or in parallel or in series parallel. It is time now to extend this concept to general networks in which the connections are more complicated than is or parallel.

If there are 2 elements in series, you can always combine them, if there are 2 resistance in series, you can combine them into a single resistance. If there is an inductor and a capacitor in series, you can find a single impedance by combining, by adding the 2 impedances. Similarly for parallel networks. Now in general, in making these simplifications for analysing complicated circuits which cannot be done by inspection, several theorems are useful.

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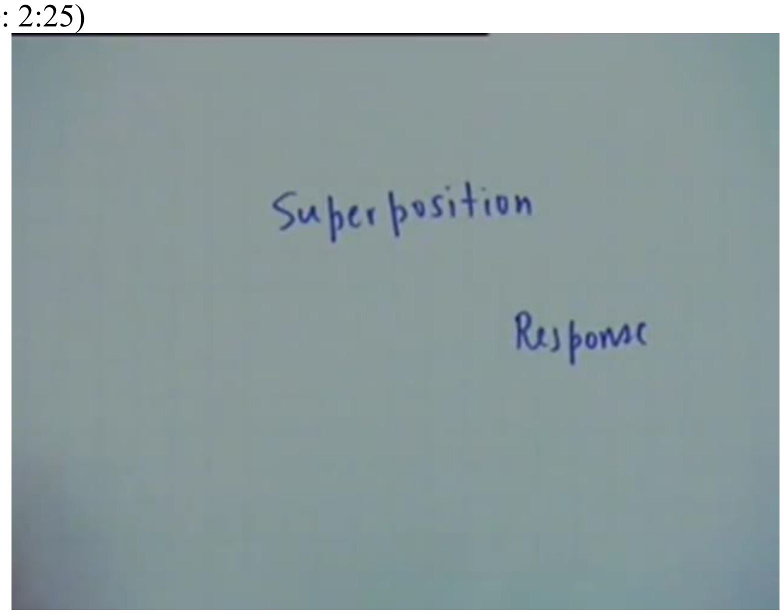

And one of them is the so-called superposition theorem. Superposition theorem when it was stated, we had not made any constraint on the nature of the elements whether they are resistive, inductive or capacitive or even with active elements, superposition always holds. In other words, the response due to a number of sources, response due to a number of sources is equal to the superposition or the algebraic addition of the responses due to individual sources with all other sources killed. Killed means that if it is a voltage source, ideal voltage source, it should be short-circuited.

If it is an ideal current source, it should be open circuited but there is one class of sources which you must leave intact. What are they? The dependent sources. Very good. We shall illustrate, we know that superposition holds for all kinds of soaps but we shall illustrate this with the help of a simple example.

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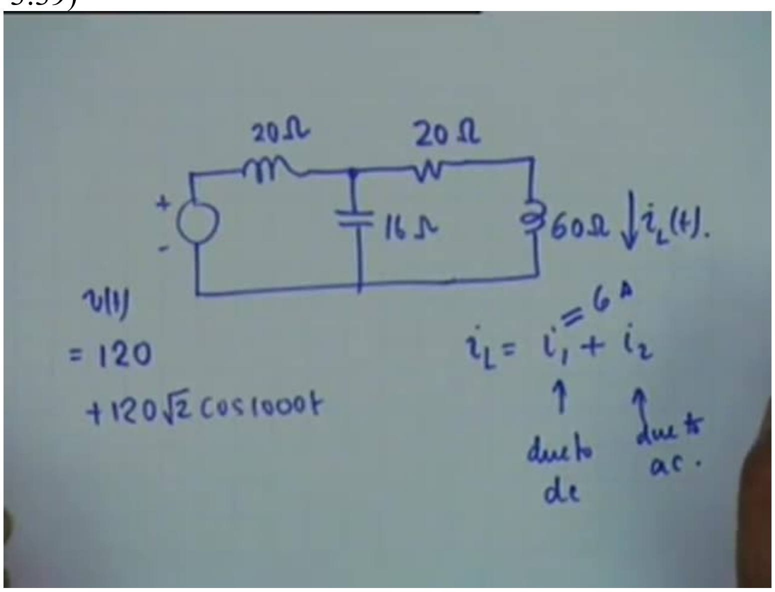

This example I have taken it from the book. We have a voltage source V of T which consists of a DC voltage, 120 + an AC 120 root 2 cosine of 1000 T, this is one of the problems in the tutorial sheet in fact. And then, we have an inductance whosereactance is specified and therefore its impedance shall be, if it is inductance, then the impedance shall be J times 20. And obviously, this impedance is valid only at the given frequency of interest, that is 1000 radians per second. And then we have a 16 ohms, whenever a capacitance and it is reactanceis specified, you have to, it is your responsibility to insert the sign.

The impedance of this obviously shall be - J 16 and then you have in 20 ohm resistance and a 60 ohm reactance induct and it is this current IL of T which is of interest all right? Since the source and we want to do this by calculating by utilizing the theorem of superposition or the superposition theorem. Since the source consists of 2 sources, one is 120, a DC and the other an AC, we can find out the response IL in two steps. That is, I write IL as I1 + I2. I1 due to the DC source and I2 due to the AC source and we can combine the 2. As far as DC is concerned you notice that this is a short-circuit, inductor. The capacitor is an open circuit and this inductor is a short-circuit and therefore I1, you can very easily see is 120 divided by 20 ohms that is I1 is 6 amperes. To find out I2 now, you forget about the DC part and because it is a pure AC, you can apply the phaser relationship.

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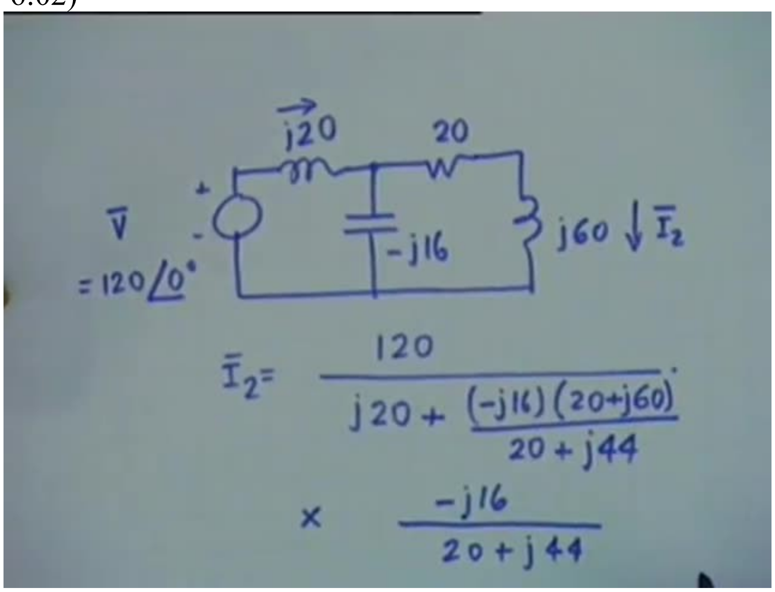

And if I draw the phaser equivalent circuit, what I shall have is a voltage phaser which is 120, the RMS value, angle 0 degree, then we have now you talk in terms of impedance because this is what you shall have have to manipulate. J times 20 and then - J times 16 and now it is 20 and + J times 60 and this phaser is I2 all right? And I2 can now be written down by inspection. I2 can be written down by inspection, it is the voltage 120 phaser divided by the total impedance looking from here which is J 20+ the parallel combination of - J 16 and 20 + J 60. And therefore - J 16 multiplied by 20 + J 60 divided by 20 + J 60 - J 16, so 20 + J 44 multiplied by this is the total current phaser, then it makes a division between 2 branches and therefore this shall be multiplied by - the impedance of the other branch divided by total of this impedances, which is 20 + J 44 or all right? This you can write down by inspection.

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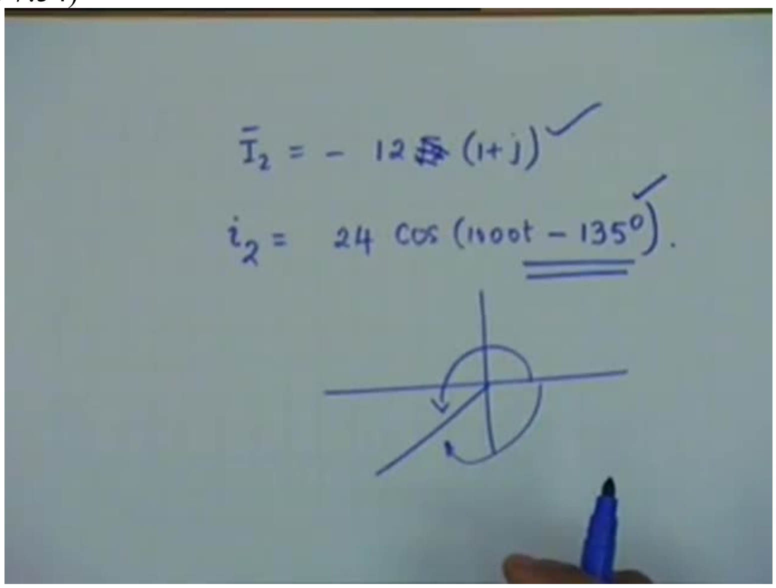

Now the next task is to simplify and if I leave the algebra to you,the final result is well, I2 bar becomes equal to - 12 root 2 1 + J. I hope I am right. Yes,- 12 root 2 1 + J. And therefore, I can write I2 as a function of time as 24.

Student: Sir 24 root 2.

Student: Sir root 2 comes from answers here.

Student: 24 root 2.

Professor: Root 2 will come from 1 + J and therefore, I think it is simply - 12 1 + J. This is the correct way. I am sorry, I made a mistake. And therefore, the peak value, the root mean square value will be 12 times root 2. Then you multiply by root 2 to find out the maximum value. So it is 24. Then you have cosine of 1000 T + now the angle.

Student: 45

Student: 45

Student: 135.

Professor: It is - 135 degrees. Explained, let me explain why it is so. The negative sign gives rise to an angle of pi and 1 + J gives rise to an angle of 45. So it is either 180 + 45 or - 180 + 45. The angles are the same,+ 225 degree and - 135 degrees all right? This angle is the same as this angles. 180 + 45 or - 180 + 45 which means - 135. And this is the correct answer. Well the answer, as far as the mathematics is concerned, both answers are correct because the angle is the same,+ 225 and - 135 but one shows that the current is leading the voltage and the other shows that the current is lagging the voltage and in this particular case, the current is indeed lagging. And therefore, this is the correct answer. I write that from physical considerations. This is the point that I wished to make in this exercise.

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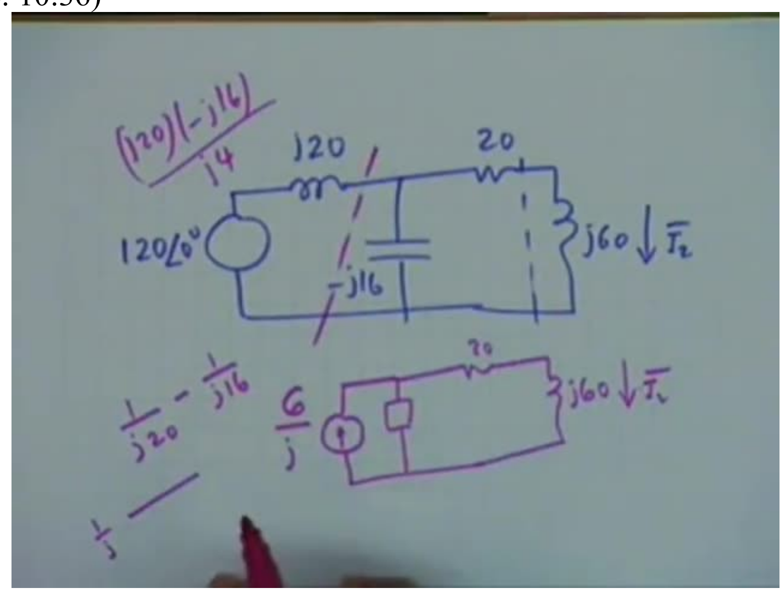

If I take the same problemnamely to find out the current, let me draw it again, 120 zero degree , J 20,- J 16, 20 and J 60 and the problem is to find out this current, I2. I could also have done this by the application of either Thevenin’s or Norton’s theorem.Thevenin’s and Norton’s theorems are valid for AC phasers also and these are also very important tools for determining the for solving a complicated network. For example, if I apply let us say Norton’s theorem,Norton’s theorem to find out this current, all right?

Then you see, you short-circuit this, find out the short-circuit current and then you find the equivalent Thevenin impedance all right? This can be done, can you suggest a better procedure? Source transformation. What we do is, we 1st apply in Norton's theorem to the left of these 2 lines. Then we get 120 zero degree divided by J 20 and therefore, it would be 6 divided by J, this is a current source all right? If I apply in Norton's to the left of this, current source in parallel to J 20. This comes in parallel - J 16 and therefore the equivalent admittance, J 20 and not the sum of the 2. We have to take the admittance and then take the sum.

Therefore, 1 by J 20 - J 16 which is 1 by J, yes you can simplify this. Whatever the result is, that is what you have to put here, a single admittance. Is this clear? J 20 impedance comes in parallel with - J 16 whose equivalent impedance would be, you can either calculate by admittances or by impedance. For example, J 20 multiplied by - J 16 divided by J 4, this is the equivalent impedance all right? Then you have the 20 ohms and J 60 all right? You could now apply the formula for division of current directly is not it right? There is a current source which divides into 2 parts, this one and this one and therefore you could write the current I2 phaser directly from the circuit.

By inspection, nothing is to be solved. All that we are doing now is almost by inspection. We are not solving any differential equation, we are not making even large-scale algebraic simplifications. We are going almost by inspection. This is the beauty of the phaser analysis that it affords network analysis almost by inspection.

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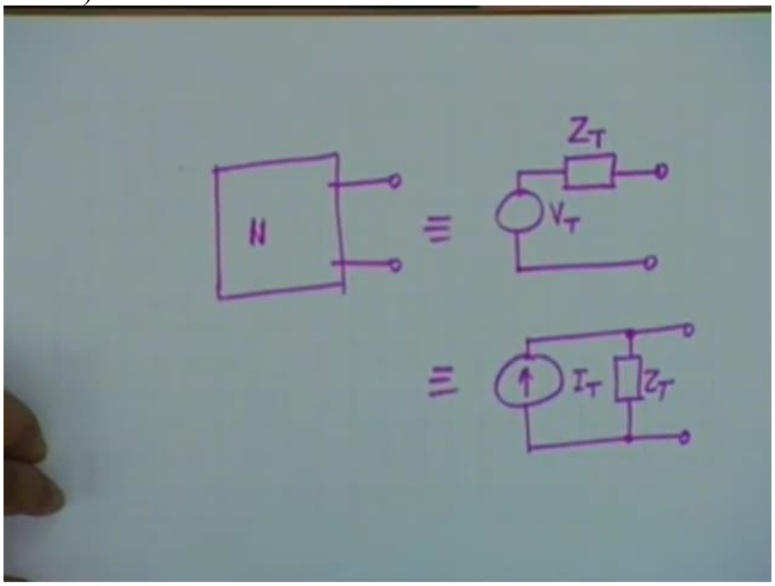

So the end result is that givenany network N which consists of sources and linear elements, wellThevenin's theorem says that it can be reduced to a voltage source VT in series with not a resistance now because it could contain inductance, capacitance and resistance and therefore, some impedance ZT. This is equivalent to this or you could also work in terms of IT, the Norton equivalence in parallel with the same impedance ZT all right? And as I said this affords a simplification, tremendous simplification. And whether it is DC or AC, it does not matter. If it is a combination, well you can work in terms of superposition. All right?

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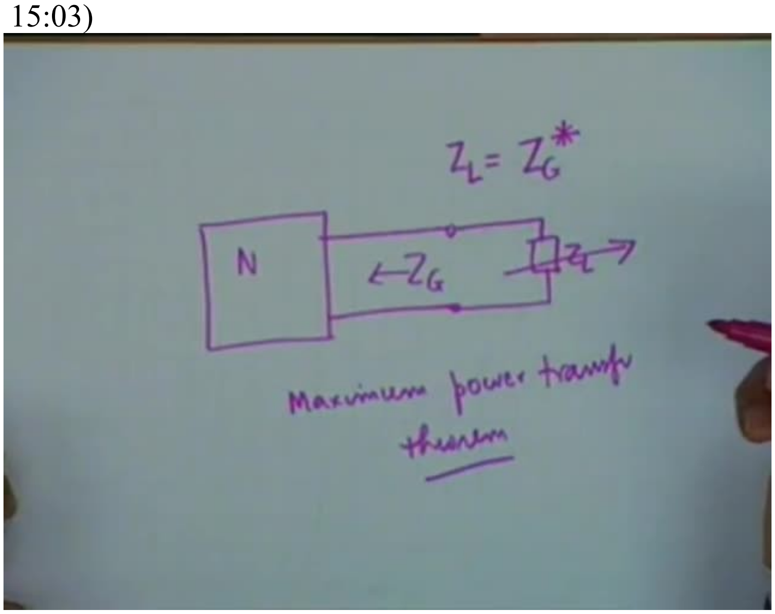

The point is, if you have a load to be connected to the network N, if you have a load let us say ZL, we ask the question, under what conditionif you have a load ZL which is fixed, now if you have a load ZL which let us say varies. The network is fixed, the network contains sources and inductance, capacitances all right? Under what condition will the load absorb the maximum possible power from the network? And thisis in the literature known as the maximum power transfer theorem or simply, maximum power theorem all right?

It is very easy, it is very easy to show that if the network was resistive, then the load should also be purely resistive and should be equal to the Thevenin equivalent resistance of the network. This is the condition for maximum power transfer. If capital N is resistive all right? If capital N contains resistances as well as reactance is, then the condition is that the load ZL if the Thevenin equivalent resistance is Z sub G, then ZL should be thecomplex conjugate of the equivalentThevenin impedance. And this is what we are going to prove in a few lines. We willtake a shortcut to the proof and these are some tricks of the trade.

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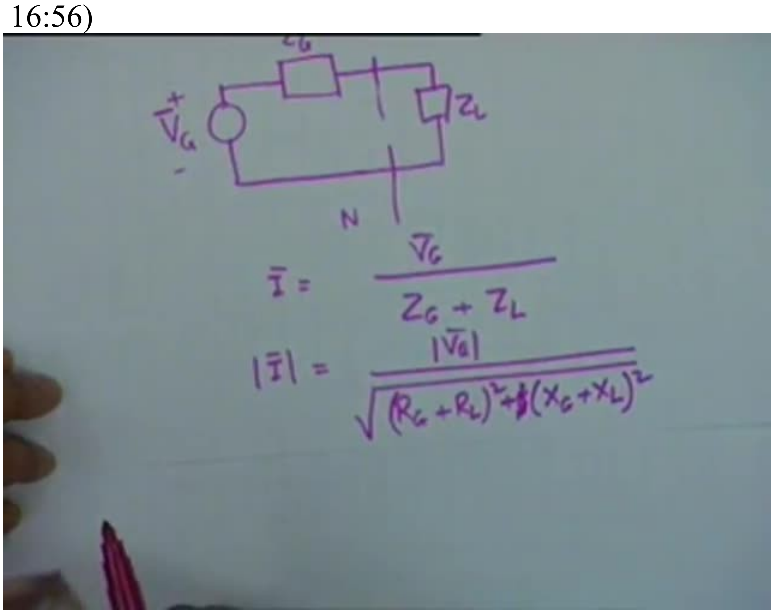

And let us replace the network N by a voltage source VG and then impedance Z sub G. Well, this is a phaser. And we connect it to the load ZL, then the currentin the circuit I, this represents the network N, this is theThevenin equivalent. The current in this, current phaser in the circuit is VG phaser divided by Z sub G + ZL all right? So that the magnitude of the current, magnitude of the phaser is given by magnitude of the voltage phaser divided by square root of RG + RL, now we are breaking upthe impedances into their real and imaginary parts, that is resistive and reactive parts.+ J times XG + XL. I beg your pardon, square of this because we are finding out the current. All right? Let me write it down again.

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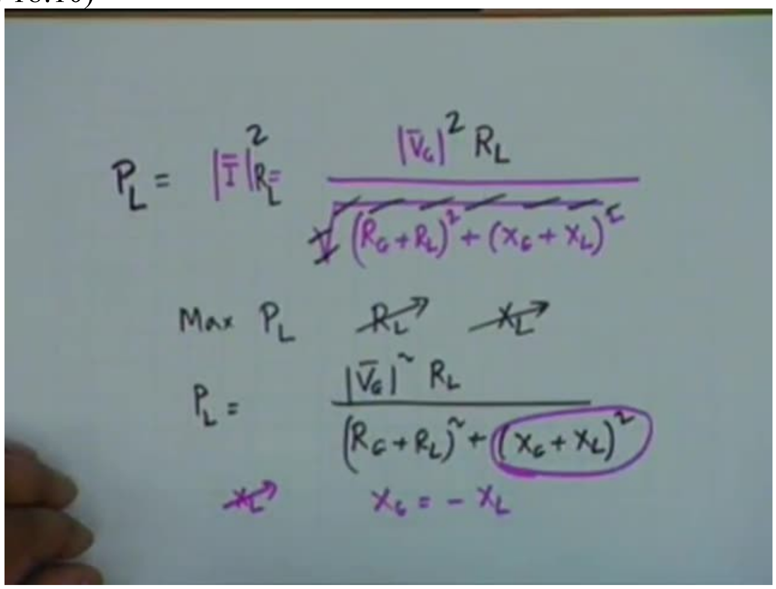

The current phaser magnitude is equal to the voltage phaser magnitude divided by square root of RG + RL whole square + XG + XL whole square. So if I wish to find out the current, the power absorbed by the load, well the power would be absorbed by the resistive component of the load. Power would be absorbed by the resistive component of the load, power is stored in the reactive components of the load. So the power absorbed by the , if I call this PL would be simply this squared, current squared multiplied by the resistive component of the load which is RL and therefore what will happen is, this will be squared, it will be multiplied by RL and this square root shall go.

This will be the expression for power all right? And we wish to maximise this power. The problem now is, maximise PL by varying the load, that is RL and XL.Let me write it down clearly. VG Square RL divided by RG + RL whole square + XG + XL whole square. Since there are 2 variables, namelythe resistive part of the load and the reactive part of the load , PL is a multi-variable function. It is a function of 2 variables all right? And therefore any maximisation that I do shall require partial differentiation but I want to avoid all this by applying a little bit of trick. The trick is, I argue let us 1st look at XL lets keep RL constant, let us vary XL. This is what we mean by partial differentiation. In partial differentiation, one of the variables is assumed constant, you differentiate with respect to the other. So if I concentrate on my attention on XL, you notice that this PL is a monotonically decreasing function of XL, that is you increase XL, PL diseases. And therefore PL will be maximized if XL is the variable, PL will be maximised when XG is equal to - XL, that is the minimum value that this expression can take is 0 and it happens when XG is equal to - XL. That is, if the source is inductive, then the load should be capacitive, the reactances should be equal and opposite of each other. On the other hand, if the source is a capacitive, then the load should be inductive.

This is the only way that they can cancel each other and therefore one of the conditions is therefore that XG is equal to - XL. And then, under this condition, we have not got the maximum power but a sub-optimum because wehave attacked only one variable, we have attacked with only one weapon whereas we have 2 in our hands. All right?

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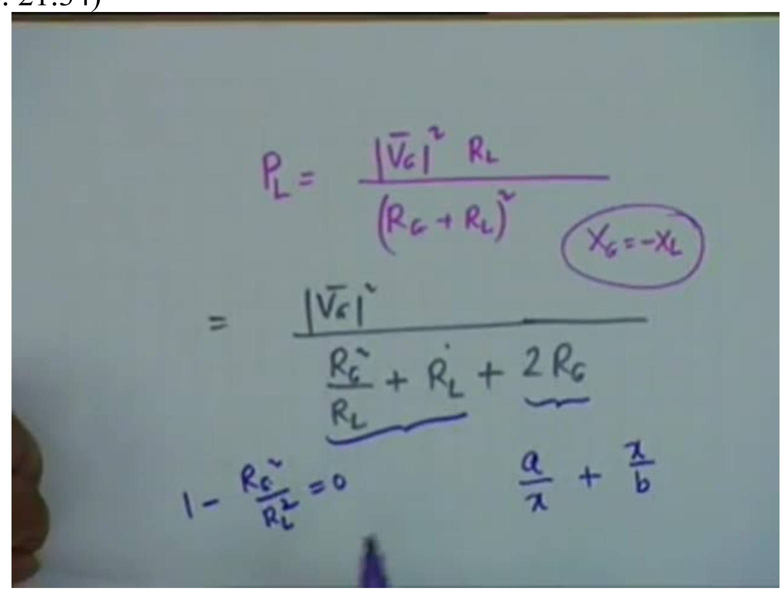

One weapon has given us the intermediate expression which is VG Square RL divided by RG + RL whole square. This has been obtained under the condition that XG equal to- XL. Now we argue, how do I maximise with respect to RL? I can again differentiate and put the result equal to 0 but a shortcut is this and I want you to remember this. I can write this as VG Squared, now I expand this and divide by RL so that the variable is brought completely into the dominator. So I get RG squared by RL + RL squared divided by RL. So it would be simply RL + twice RG RL divided by RL.

So twice RG of which you see this quantity is a constant this and this is the thing that is variable. Whenever you have an expression of this form, A by X + X by B, that is whenever, this you should remember throughout your life that whenever you have an expression in which the variable, one of the components increases with the variable, the other component decreases, then the optimum, that means the minimum is obtained when the 2 are equal. You can verify this by differentiation. That is DD RL of this expression would be 1 - RG squared divided by RL Square and if you put this equal to 0, obviously what you get is RG equal to RL. Is that all right?

No differentiation is needed. If you can put it in this form, then the minimum value of this, not maximum mind you. Maximum obviously is infinity, when RL goes to infinity, the maximum is infinity. Or RL goes to 0. Maxima occurs at both extremes, RL equal to 0, RL to infinity, in either case the power absorbed is 0 however. Is that is that clear why? If the load is short-circuit, it cannot absorb any power. If the load is open, no current can flow. So no power can and therefore, this quantity is a minimum when RG equal to RL and therefore, the power is the maximum.

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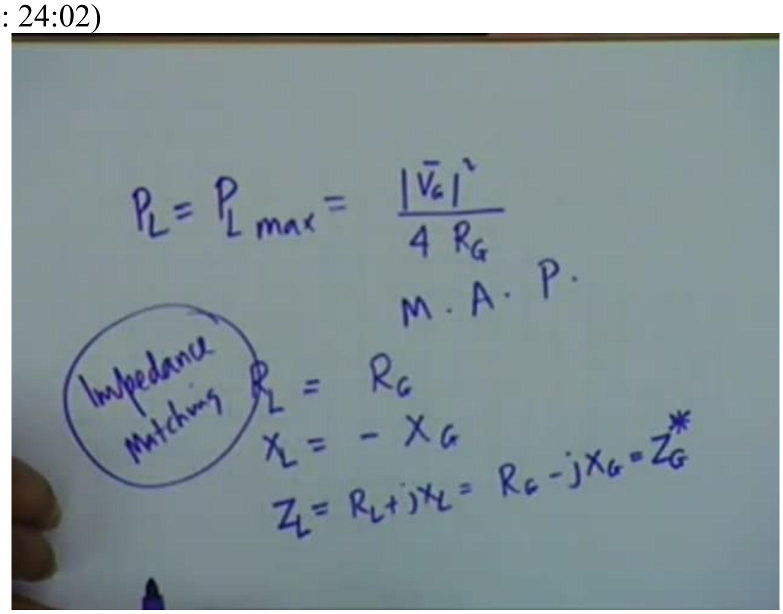

And therefore we can write PL Max, PL equal to PL Max equal to VG squared. If you put RG equal to RL, then you getVG squared by 4 RG why? Because RG equal to RL. So twice RG whole square is 4 RG squared and cancels with RL. So 4RG and this is called the M A P, the maximum available power from the source. You cannot draw more than this. Under no circumstances can you draw more power than this and this happens when RL equals to RG and XL equal to - XJ. In other words, ZL which is RL + J XL. RL + J XL is simply equal to RG - JXG which is equal to the complex conjugate of the source impedance and this is one of the most important theorems in electrical engineering, maximum power transfer.

Wherever the power is limited to, wherever the power is limited, for example the exacta signal received through communication receiver, whenever the power is limited, you should try to draw the maximum available power by matching this is called impedance matching that is by taking a load, by designing the receiver in such a manner that it matches the antenna through which the signal is received. Well, the antenna can be considered as a signal source becauseit absorbs the radiation from the atmosphere and then pass it to your receiver and thisprocess is known as impedance matching.

Impedance matching is not of importance in for an example, lighting of this room or in drawing power for the refrigerator, you do not match the impedances. Why? Because what is of concern there is efficiency. In such cases where maximum power is required, we do not care about efficiency. What is the efficiency under this condition when maximum power is being drawn? The maximum available power is this and equivalent amount of power is being absorbed in the source. Is not that right. You see the source delivers through a resistance to a load RL and when the load and source are matched, that is one is the complex conjugate of the other, RL absorbs this amount of power.

This amount of power must then be absorbed by RG also. So half of the power is wasted in the source. We do not want this for an ordinary domestic supply for example. We do not want this. We want efficiency and therefore where efficiency is not important, impedance matching becomes extremely important. And this is one of the most important theorems of electrical engineering and finds application almost everywhere in all fields of electrical engineering.

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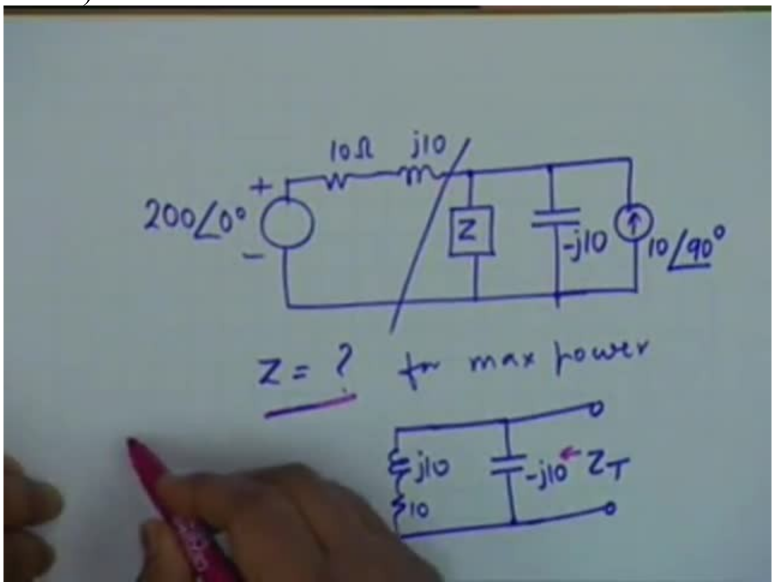

Let me illustrate this with the help of a problem. I have a source 200 zero degree and an impedance consisting of 10 ohms and J 10 which means an inductive reactance and my load is here. My load is this Z which is shunted by a reactance of, an impedance of - J 10 which is that of a capacitor and a current source which is 10 angle 90 all right? The question is, what should this impedance beso that it absorbs the maximum available power? Now you notice that here, there are 2 sources, not one. One fine point is that these both of these sources, when I write sources like this, what is the information that is hidden in this?

Student: (())(28:32)

Professor: Pardon me.

Student: Source transformation.

Professor: They can become?

Student: They can be combined.

Professor: They can be combined.

Student: They have the same omega.

Professor: They have the same?

Student: omega.

Professor: That is correct. This is the information that is hidden. Well, you can combine sources in many ways but whenever we write like this, it means that they are at the same frequency. Otherwise the phase shall be different. Not only that, if there are 2 sources of different frequencies, they cannot be combined. Rajat’s answer is also correct to some extent that they can be combined but they can be combined, one of the necessary conditions not sufficient, one of the necessary conditions is that they must be of the same frequency, all right.

Student: Can we combine in this case?

Professor: Yes, of course.

Of course we will apply Norton’s to the left of thisand I shall combine that current generator with this current generator surely, no problem. But the question here is different. Do I have to combine? No. The question is what is Z for maximum power absorption by Z, for maximum power in the load? All that we require is to find out theThevenin equivalent impedance which means, what is this impedance? It is simply J 10, then 10 ohms, the source is to be killed in parallel with - J 10.

That is all. Now if you apply, if you think blindly, nowone can think while one closes his eyes. So thinking blindly is not an impossibility but do not do so. Look at the problem carefully. You do not need to find, you do not need to combine sources because all that is asked is, what should be the value of Z so that maximum power is absorbed?

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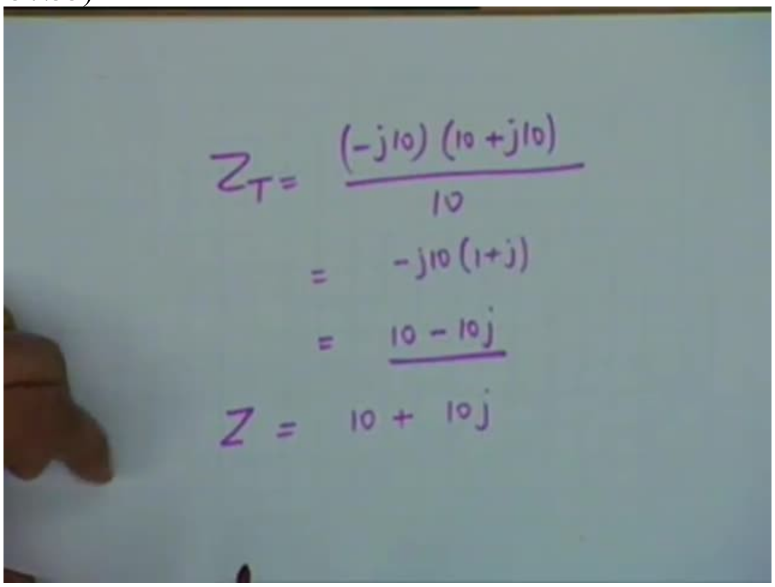

So you find out ZT obviously your ZT is - J 10 multiplied by 10 + J 10 divided by 10 all right? 10 + J 10,- J 10, theycancel each other. So you get - J 10 1 + J which is equal to 10 - 10 J. Is that okay? Therefore all that you need is Z should be equal to 10 + 10 J. In other words, the source is now capacitive when the reactance is negative. And therefore your load should be inductive and they should match each other. The resistive components should be equal, the reactive components should be equal and opposite of each other. Let us look at something else. No we are going to the enunciation of another theorem which we have not been familiar with so far.

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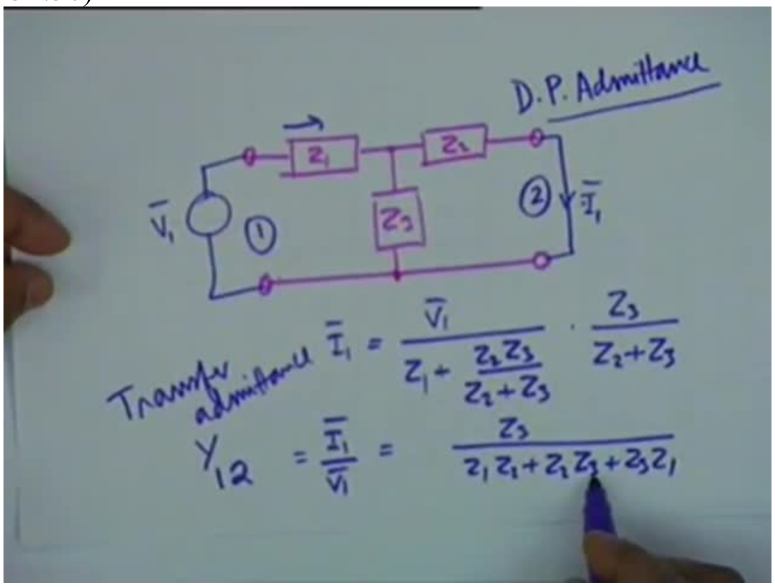

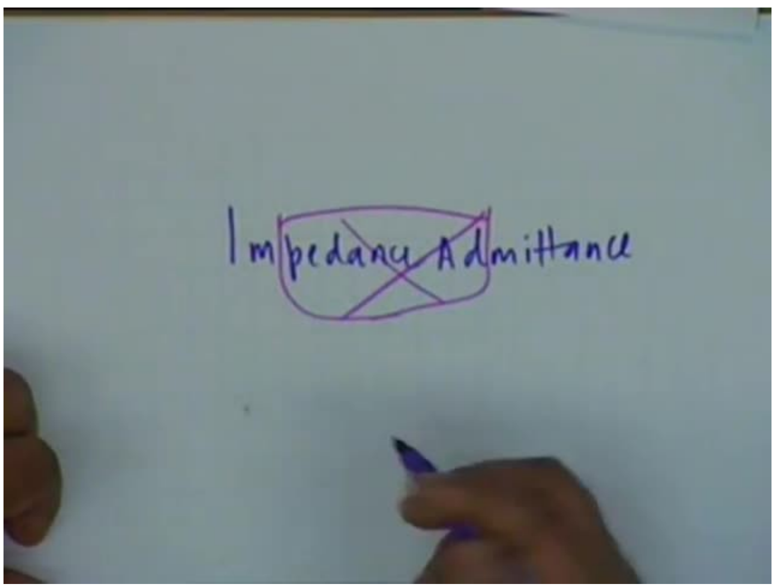

Let us look at a typical problem. Let us say we have a network like this.what would you call this network? It is a two port. How many ports? 1 and 2 but it is also a 3 terminal network because there are only 3 terminals, 1, 2 and 3. This terminal is common between input and output all right? Now let us apply a voltage source here, V1 and let us find out the short circuit current I1 here all right? Obviously I can find out I1 by inspection. It is V1 divided by Z1 + Z2Z3 divided by Z2 + Z3, this is the total current. Then I take current division between Z3 and Z2 and therefore this is Z3 divided by Z2 + Z3 agree? Is that okay? All right.

So thereforeI1 by V1 is equal to well you can see that it is Z3 divided by Z1 Z2 + Z2 Z3 + Z3Z1. Is that okay? Is this algebra all right?. Now let me give a name to this quantity. That is why the current, the current is obtained here at a port which is different from the exciting work. The excitation is at Port 1 and the current, the response is obtainedat Port 2. The ratio of the response to the excitation is now an admittance. Is it that right? The response is a current and the excitation is a voltage and therefore current to voltage has the dimension of admittance and this is called a transfer admittance, transfer because the current response is obtained at a different port and the symbolic that is used for it is Y12.

That is, this is the exciting port, port 1 and the current is obtained at Port 2. There are different conventions. Y12 is the response obtained, the current response at Port 2 divided by the voltage excitation at Port 1. And it is called transfer admittance. You understand the meaning of transfer. If it was not transfer, if you had applied the voltageat a port and measured the current at the same port, then you simply call this an admittance or sometimes to distinguish between transfer admittance and simple admittance, we may also call the latter as driving point admittance, that means admittance is measured at the port at which you are driving all right?

If the excitation and response are at the same point, then the ratio of the response to excitation, there is nothing sacred about voltage excitation. You could also have a current excitation and measure the voltage all right? Thenthe response to excitation would have been an impedance all right? So these are called driving point impedance or driving point admittance in contrast to transfer impedance. Here also I could have a voltage generator, I could have a current generator here and I could have measured the open circuit voltage. So in that case, we have been transferred impedance all right?

Transfer impedance and driving point impedance, these are 2 different kinds of quantities. Although dimensionally, they are the same. If it is impedance, then it is measured in ohms, if it is admittance, then it is measured in mhos but but physically, they are different quantities because the response is measured at a different port in the case of transfer, impedance or admittance. Did I tell you the common name for impedance and admittance? Immitance and this is derived like this, impedance,admittance.

What we do is we eat away a part of it. So this part is eaten away. So if we mean, if we can if we want to say transfer impedance or admittance, we will say transferImmitance all right? Or driving point Immitance. Now let me go back to the circuit. I found out here that the transfer admitted as obtained as Z3 divided by Z1Z2+ Z2Z3+ Z3Z1. Now let us interchange the source, the excitation in the response ports.

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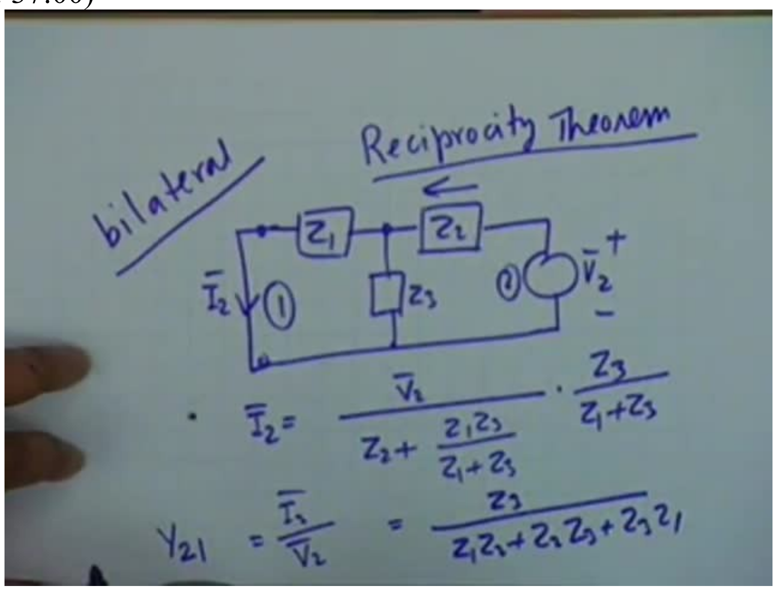

Let us interchange, that means I have the same network, Z1, Z2 and Z3, I apply the voltage source here. Let us say, a different voltage source, V2 and the response is obtained at Port 1, let us call this as current I2. Do you see what I have done? I have simply taken, I simply interchanged the the excitation and the response points. Initially, the source was a voltage source was here and this was short-circuited. Now after I transferred the voltage source to port 2 and I am measuring the current at Port 1.Now can you find out I2 bar? In the same way, it is V2 bar divided by Z2 + Z1Z3 divided by Z1 + Z3. This is the current through Z2. It will come to be the same, that is correct.

This will be Z3 divided by Z1 + Z3 and you see that I2 divided by V2, what should WE call this now? Y21. Is that correct? 21, yes. Thesource at Port 2 and the response at Port 1 and you see that surprisingly, this is the same. This is the same as in the previous case. All right? And this is whatis generalised to atheorem called the theorem of reciprocity or reciprocity theorem.Reciprocity theorem. It, in general terms, it simply means the following. That ifs there is a network if there is a network which contains bilateral elements, let me introduce this term, bilateral, that is elements which conduct equally well in both directions.

A resistance, it does not matter whether one end is positive or one end is negative. If the same voltage is applied, the same currents would flow. And a resistance conducts equally in both directions. Similarly, an inductance, similarly a capacitance. But you know at least one case, one element which defies this, that is a diode. So if a network does not contain unilateral elements like a diode, if it contains only bilateral elements, then the network is said to be reciprocal. That is if the excitation and the response are interchanged, then the ratio remains the same. All right?

This is called the theorem of reciprocity or the reciprocity theorem and in the context, one must remember that the network shall should not contain any element which is partial to polarity which is partial to polarity. For example, a diode if it is forward biased, it conducts easily. If it is reverse biased, it does not conduct.

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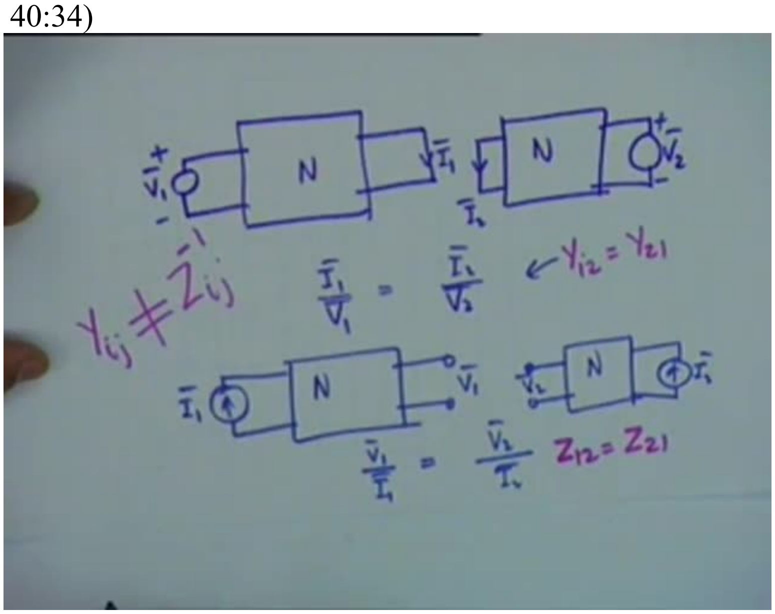

And in general , the reciprocity theorem is stated like this. You have a network N which is a reciprocal network. Any network which obeys reciprocity theorem is called a reciprocal network but then you cannot define reciprocity theorem in terms of reciprocal network. So you say N containslinear elements, linear and bilateral elements.N contains only linear and bilateral elements, it is a 2 port network and therefore if you apply a voltage source, I am going to ask you a question.

Now if you apply the voltage source here and measure the current, the same network if you measure the current here, due to a voltage source here, well the ratio is the same, that is I1 by V1 is equal toI2 by V2, that is the transfer admittances are the same, then the network N, well this is a statement of the reciprocity theorem that if the excitation and the response are interchanged, there is no change in the ratio. All right? If this is one vote and this is one ampere, this is 50 ampere, then this should be 50 ampere. The ratio shall be the same. Now I am asking you a question. Look at the question carefully.

Suppose, well under this condition, suppose I apply a current generator all right? Let us say I1 and I measure the voltage V1 here, similarly I apply a current generator I2 here and measure the voltage response V2. By reciprocity theorem, the ratio from these the same. That is,response to excitation should be equal to the response to excitation. If N is a linear network with bilateral elements, then the ratio of the response to excitation should be the same as the ratio of the response to excitation. If I call this, if I characterise this in terms of transfer admittances, response is a current, excitation is a voltage. Current to voltage is admittance andcurrent and voltage are at different ports.

And therefore we say Y12 is equal to Y21. Then what should we call this? Transfer impedances, Z12 should be equal to Z21. The question that I ask is, is there a relationship between Y12 and Z12. They are reciprocals of each other? Much to your frustration, they are not. They are not and this is something which we wish to investigate. What is the relationship between them? They are not simply the reciprocals of each other. Why? What is the reason? The reason is that the conditions here are quite different from conditions here. There is a short-circuit and there is a open circuit.

They are dual situations all right but they are not, the impedance and admittance are not reciprocals of each other. One must remember this that YIJ is not equal to ZIJ. Transfer impedance okay. All right? This must be remembered because this is a mistake very often committed even by graduate electrical engineers. So you should be particularly careful about this.

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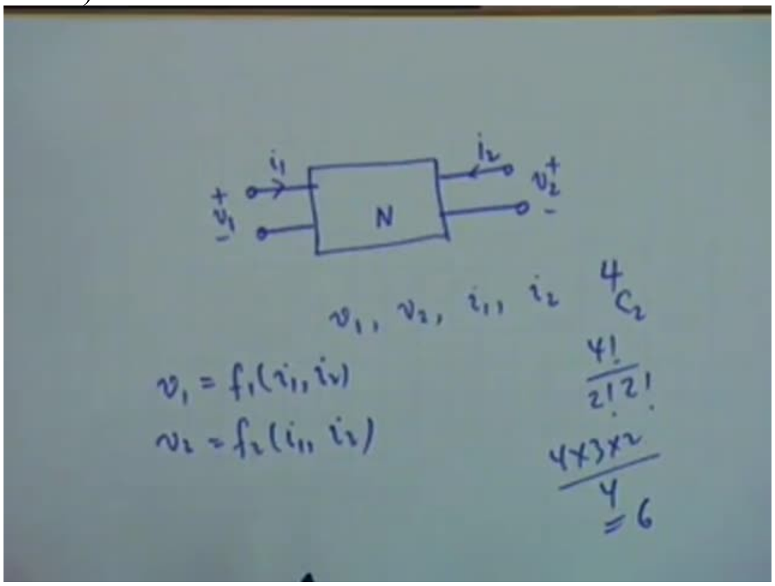

To investigate this point, relationship between the transfer admittances, we consider a two port in general. Let us say, capital N is a 2 port, a general 2 port where what you can do is, you can apply a voltage. What are the things that you can do? You can apply two voltage sources and measure the currents. You cannot reach inside the network. You have only two ports all right? So what you can do is, you can apply two voltage sources, measure the current. Or you can apply two current sources and measure the voltages. Or you can apply a combination, one of them can be a voltage source, the other can be a current source and you can measure one voltage and one current.

The point, the fact of the matter is that there are 4 quantities, V1, V2, I1 and I2 of which 2 can be specified independently. The other 2 then shall be determined from the characteristic of the network N. Is this clear? There are 4 quantities, 4 parameters,4 variables of which 2 can be independently specified. Other 2 will be determined by theby the characteristics of the network. In how many ways can you specify the Independent and the dependent variables? Obviously, there are 6 ways. 4C2, 2 taken out of 4.

Factorial 4 divided by factorial 2 factorial 2 which is 4 times 3 times 2 divide by 4, so 6 ways all right? Now 6 ways means what? You can say V1 and V2 can be a set of dependent variables. V1 can be let us say F1II1I2,V2 can be F2I1I2. These are independent variables, I1 and I2 and v1 and V2 are dependent variables or you can write I1 and I2 in terms of V1 and V2, two voltage sources and then you find the dependent currents or you make a combination is V1I1, V2I2, you can make V1I2, V2I1 or their permutations. You can have V1I1 or you can have I1V1 all right? That is also a possibility.

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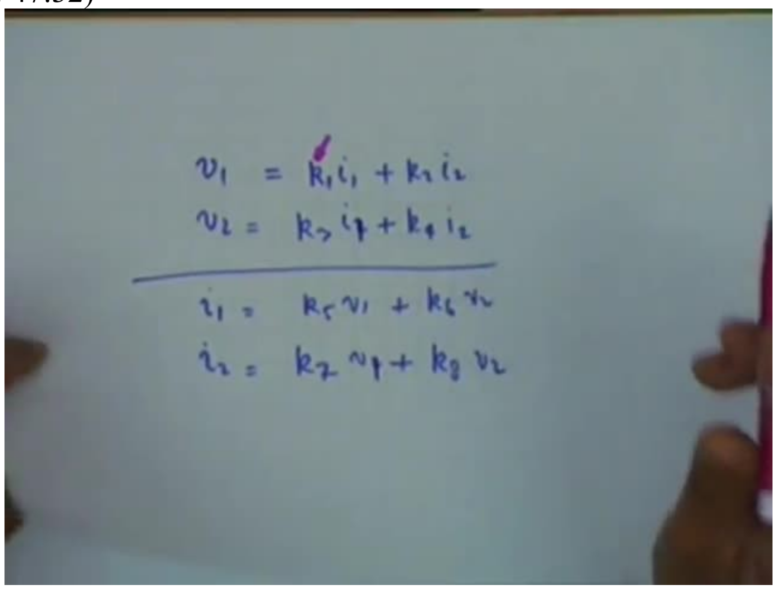

There are in all 6 ways. But at the present time at the present time we shall concern ourselves with only 2 of these representations, that is V1V2 in terms of I1I2. Or the other way round, that is I1I2 in terms of V1 V2 all right? And since the network what we mean is, V1 is expressed as a function of I1 and I2, V2 is expressed as a function of I1 and I2 or I1 is expressed in terms of V1 and V2, I2 expressed in terms ofV1 and V2 all right? Now the network is linear. The network is linear and thereforeV1 shall be of the form K1I1+ K2I2 and V2 shall be of the form K3I1 + K4 I2. All right?

It is a linear network and therefore the voltage and the current, the voltagewhich is a dependent variable, must be a linear combination of I1 and I2. That is if pardon me? Superposition. That is it. I1 and I2 are Independent variables, they are sources and therefore you can determine the responses to each independently and add them up. Similarly, you can write I1 equal to K5V1 + K6V2 and I2 as K7V1 + K8V2 all right? Now if the network is excited bysinusoids that is AC sources, then a special form of these relation relationships are valid and these special forms can be obtained by a very simple consideration. What is theof K1? It must be impedance.

Student: Impedance

Student: Impedance

Student: Impedance

Professor: Impedance.

Similarly K2, K3, K4 all of them should be impedance. Agreed?

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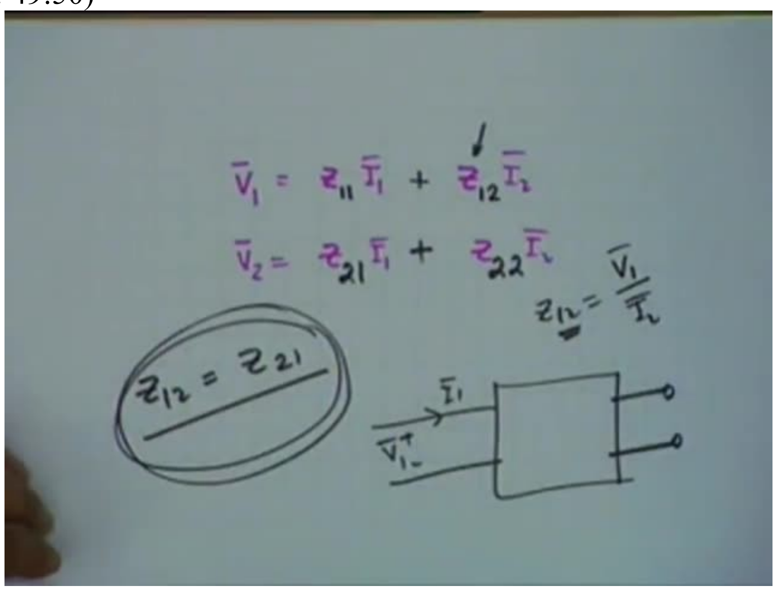

So what I do is if we take this, if we take the 1st set of relationships where I1 and I2 are dependent variables andV1 and V2 are dependent variables, then we say, the voltage phaserV1 and the voltage phaser V2 can be written as in terms ofI1 and I2, similarlyI1 and I2 and the coefficients are impedances. So we shall have Z, Z, Z, Z. We must now specify all all Zs we must now distinguish between the 4 Zs all right? Now what shall we call this?what shall we call this Z for example? Well, we call this Z11 and the reason is the following. The reason is that, what is Z11? It is V1 divided by I1 with I2 equal to 0.

Now V1 by I1 means that you are measuring the response at the same port as the excitation. Is not that right? If you recall, this is port 1, this isV1 and this is I1. What you are doing is you are makingI2 equal to 0. I2 equal to 0 means these are left open circuit and therefore, if you are applying a current source here and measuring the voltage. Is not this a driving point impedance? Driving point impedance. And since it is measured at Port 1, we call it Z11. Question is, why two subscripts? Why two subscripts are needed?

Because the transfer impedances required two subscripts. So to keep uniformity, we maintain 2 subscripts for the driving point impedances also. And from the same consideration, this will be called Z12 the current is measured at port 2. Okay. Iintentionally, it is okay. If you agree, then Iwill not explain further. It is a matter of convention. This impedance is called Z12. If I had introduced a different convention, go back and change it. All right. What should we call this? No. Before we go to the other one,

Student: Sir but I2 is the independent one.

Student: Yes sir, so it should be Z2.

Professor:Okay, I2 is the dependent variable and I am measuring V1.

Under what conditions? I1 equal to 0. So Z12 is equal to V1 divided by I2 all right? And we call this Z12, that is from response at Port 1 and excitation at Port 2. If I had used a different nomenclature earlier, go ahead and change it all right? This is the IEEE accepted terminology, universal terminology. Similarly, this impedance we shall call Z21 and this impedance we shall call Z22. You understand why double subscripts? Z We could have called this Z1, we could have called this Z2 but since we we have to use double subscripts for the transfer impedances, we maintain uniformity.

And you say that if the network is reciprocal, if the network is reciprocal, then what is the condition? Z12 should be equal to Z21 all right? If the network is reciprocal, if the reciprocity theorem is obeyed, then this should be satisfied. What does this mean? That in order to describe a 2 port, we do not require 4 parameters. We require only 3 provided the network is reciprocal. Suppose this network has a transistor. Transistor can be considered as a combination of diodes + an amplifying element which are unilateral elements and therefore, it will not be valid there.

In the case of a transistor amplifier, Z12 equal to Z21 is not valid. They are quite different. One is much larger than the other. But in the case of a passive reciprocal network, that is a network containing linear and bilateral elements, this shall always be valid. Tomorrow we shall consider the other kind of description, that is consideringvoltages as independent variables and currents as dependent variables and then establish a relation between Y12 and Z12.