Transmission lines and electromagnetic waves
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Lecture - 12
Impedance matching using Smith chart

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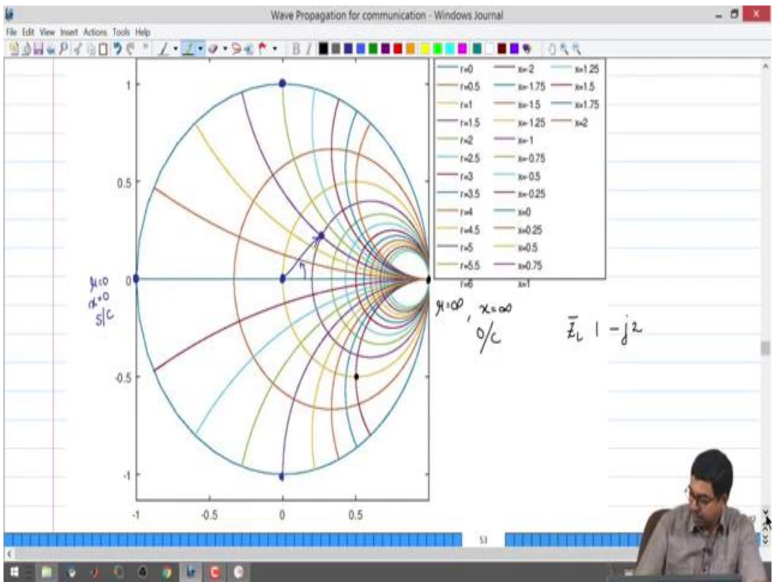

So, we will begin ok. As of now, we should be familiar with how to create our own Smith chart. There should be no issues with that. The program that we have made you should be able to create an Impedance Smith chart and an Admittance Smith chart ok. Once again, the plane in which we are seeing the Smith chart is a constant γ plane all right. The x axis is the real part of γ, which is the reflection coefficient; y axis is the imaginary part of γ ok. And on the right hand side, γ is going to be equal to plus 1 all right. If you see the co ordinate axis γ is going to be equal to plus 1 corresponding to the entire voltage being reflected back ok from the load side and the left hand side is γ equal to minus 1 from the analytical case, we already know that this corresponds to a short circuit condition.

So, what we had done was we had taken different values of r and x ok for the load resistance or the load impedance and by fixing x to be constant, we varied r and by fixing r to be constant, we varied x ok. When we fix r to be equal to 0 and we varied x to be going from fully capacitive to fully inductive, we ended up getting this circle ok ok. r equal to 0 corresponds to the outermost circle of the a Smith chart ok, along this circle you are just varying an imaginary part of the impedance ok. And then, as you started changing r to say a 0.5, 1 extra. So, r equal to 1 corresponds to the circle that passes through the middle of the Smith chart. The middle of the

Smith chart is a specific point that is very interesting because the reflection coefficient is equal to 0.

So, in most of the problems involving impedance matching, the goal is to navigate the Smith chart and arrive at the center of the Smith chart ok. So, this particular curve is r equal to 1 and the x changes from some minus a you know 500 to plus 500 in our court and we ended up getting this circle. So, these circles, which are going from the outer side to the right hand side and reducing in radius, are known as Constant resistance circles. In each of these circles, the value r is fixed and x is being varied ok. So, these are known as constant resistance circles.

So, given an arbitrary load impedance of the form say 1 minus j 2; suppose that your z_L normalized ok with respect to your, then the procedure for finding this particular load on the Smith chart is to take the real part, find the circle which corresponds to r equal to 1. In this case, r equal to 1 is the circle that passes through the center of the Smith chart; the yellow curve here is all right and then goes for the constant reactant circle with x equal to - 2 ok. So, x equal to - 2 is this circle right. So, x equal to - 2 will be somewhere here right. So, this will be your intersection between the two points and you mark that as z_L ok.

Once you have marked that point, the distance between the center of the Smith chart and the point that you have marked corresponding to z_L will give you the value of the reflection coefficient. Because you are in the complex γ plane. The real part of it and the imaginary part of it can be measured separately or you could also measure the magnitude of the reflection coefficient and you could take the angle from the horizontal axis and say that that will be the magnitude argument form of your reflection coefficient ok. Now, the impedance Smith chart should be abundantly clear on how to navigate ok.

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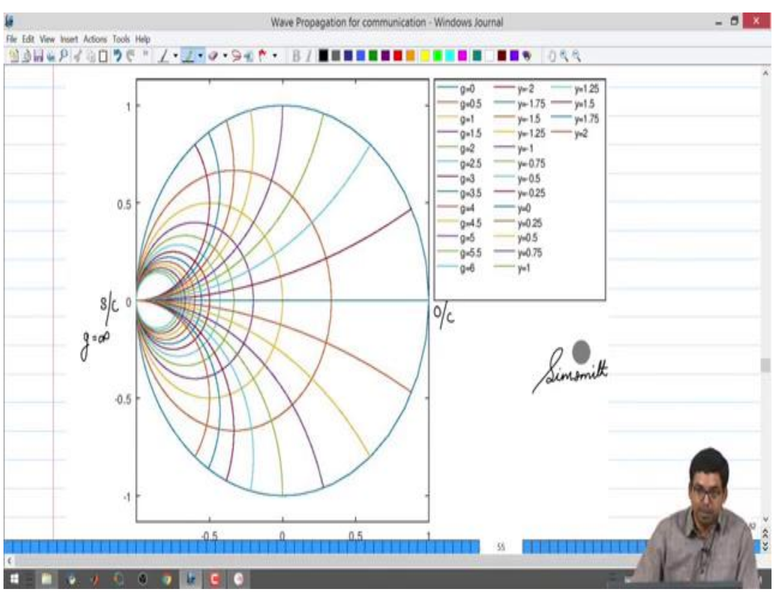

The admittance Smith chart, what we had seen was by taking the reflection coefficient in terms of load admittance ok and writing a formula for the reflection coefficient. We generated these circles. The outermost circle corresponds to g equal to 0 or the conductance equal to 0 all right and the imaginary part, which is as acceptance which is varied from negative to positive, and you end up getting a circle of constant conductance ok.

Similarly, as you keep on increasing the value of g from 0 to 0.5 to 1, 1.5 all the way up to infinity, the radius of the circle shrinks to 0 ok and the circle center itself moves to the left most position. So, you will end up getting a short circuit. This means that g is equal to infinity ok. On the left hand side, conductivity is equal to infinity means that you have short circuited your circuit all right. You could also take the imaginary part of the admittance which is going to be a susceptance and keep your a g constant and **draw** different a you know no reactances constant and the different values of g, you will end up with the curves that are flaring out.

So, these are circles of constant sum substance ok. So, given a load admittance, it will have a real part and an imaginary part. First you will find out the circle corresponding to the real part, then you will find the circle corresponding to the imaginary part; find the intersection of the two, that will give you your load admittance on the Smith chart ok. Now, one of the things that people do here is they flip this admittance Smith chart in both x and y axis so that circles exactly co inside with the impedance Smith chart and they maintain the same orientation.

The only thing that they do is if we are dealing with admittances, they will switch the open circuit short circuit condition to the left and right side and they have to keep care inductance will not be on the top capacitance will not be in the bottom. So, they will invert the x and they will invert the y axis. But nowadays, it is not necessary to do that I prefer to keep the short circuit open circuit conditions in place all right because this is an imaginary γ plane and it is tough to keep track off which axis here looking at all right. Just to be consistent we do that ok.

And today's class is more specifically how to navigate the Smith chart all right and the application that we are going to look at is given a load, how we are going to match that load using different techniques and arrive at the center of the Smith chart. This is the objective ok. So, far doing this I am going to begin by using the tool the name of the tool is going to be Simsmith ok. It is an open source free software that can be downloaded for multiple operating systems. It provides you with detailed information on manipulating RF circuits with transmission lines, loads and looking at the Smith chart interpretation. So, I am going to use this tool to demonstrate a few things ok so that it becomes clearer ok.

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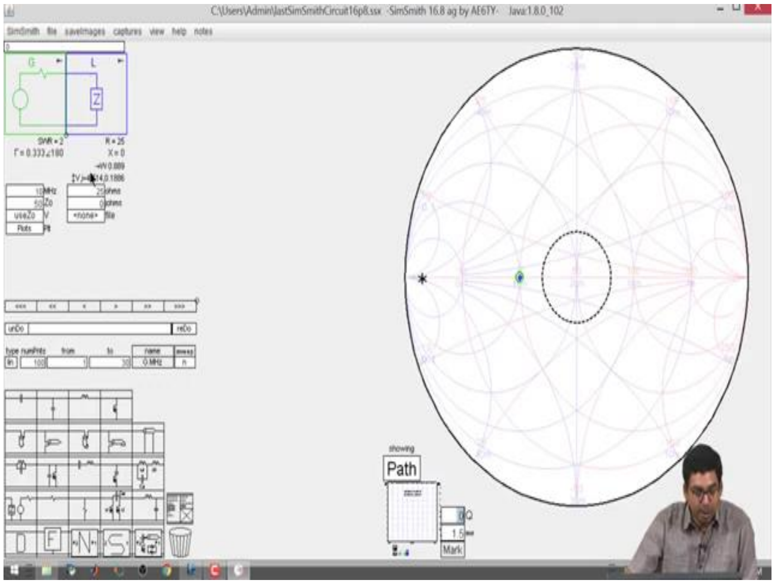

So, I will start with SimSmith and I will go for now the simplest circuit that we can have on the left hand side here corresponds to a source ok. Now, the source is a generator, usually all right and it generates some power all right. So, it does have a characteristic intrinsic impedance ok. It does not come without any impedance; it does have an intrinsic impedance ok. Let us also remember that the conventional transmission line cables also come in pre-defined characteristic impedances; it could be the 50 ohms or 75 ohms ok. So, your generators are made in such a way that the termination is 50 ohms ok.

Now, when somebody says that this a generator is going to generate say 1 watt of power, the meaning is at this end if you matched the impedance of 50 ohms, you are going to be getting 1 watt of power dissipated on the load that is the meaning. The rated power of a generator means that after your internal impedance, if you connect something on the outer part of this circuit and if this impedance is match to this impedance, then you will be getting 1 watt of power ok.

So, what I am going to do is I am going to set the parameters of the generator. I am going to tune the parameters of the load to make this point clear first ok. So, here we are not putting any transmission line, starting with really basics ok. So, I am having a 10 megahertz alternating source on the left side, it has an intrinsic impedance of 50 ohms purely resistive ok and I have connected a load and I am going to make it 50 ohms ok.

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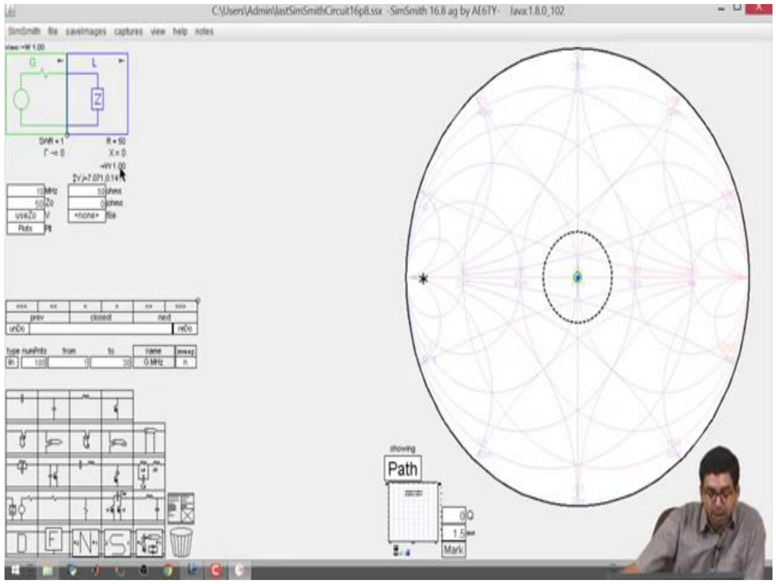

Once I make it 50 ohms the meaning is this is a 1 watt generator, it will provide me 1 watt at the load ok. So, w 1 means that I am going to be having 1 watt at the load because the impedance is matched. That is the meaning. But one could go ahead and still analyze it with more detail like we do in circuits say that there are still 2 resistances all right, maybe the generator is generating more power and the half the power is being dissipated on the load and all that.

But we have to be clear that we are not going to be creating generators with a 0 ohms internal impedance. It is going to standard and it is going to be some internal impedance and most likely it is 50 ohms ok. So, when we talk about the power on the load and impedance matching condition, we are talking about how much of power will be dissipated here and if this load is matched to this, we are going to be getting their rated power of the generator ok.

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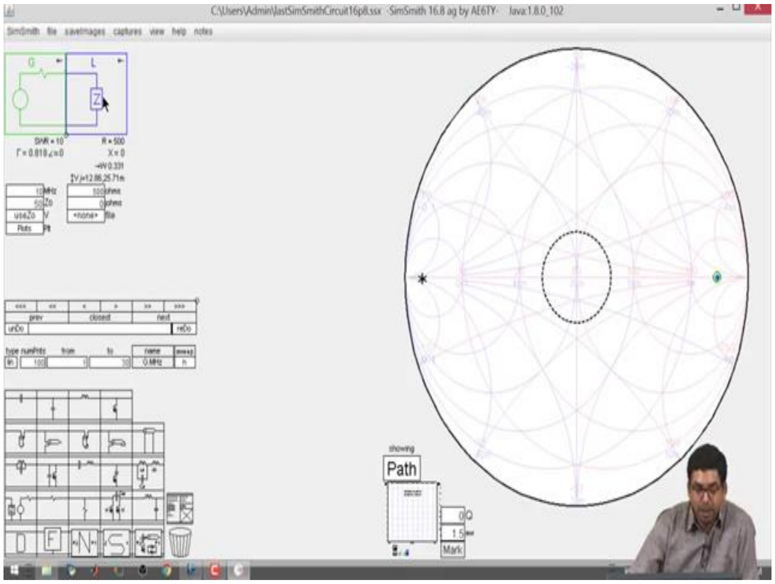

Now, you can always tweak this; you can say that you can connect 500 ohms all right. You will immediately notice that the power that is coming to the load is 0.331, which is less than 1 watt ok, and you will have a standing wave in your circuit right. It can be calculated by $\frac{z_L - z_0}{z_L + z_0}$ ok. Correspondingly, you will be having also a reflection coefficient ok. Now, if you have missed matched loads, you will not be drawing a rated power from the generator on the load ok.

So, since this is a problem relating to signals all right, power is very very critical. Signal power is critical; you cannot afford to lose single power ok. The example can be on the left hand side, there is an antenna; on the right hand side, you have a speaker or something that is processing this signal. You do not want to lose signal power anywhere else that is the whole objective. So, whatever is the rated power that we would like to get it on the load that is the objective of impedance matching ok.

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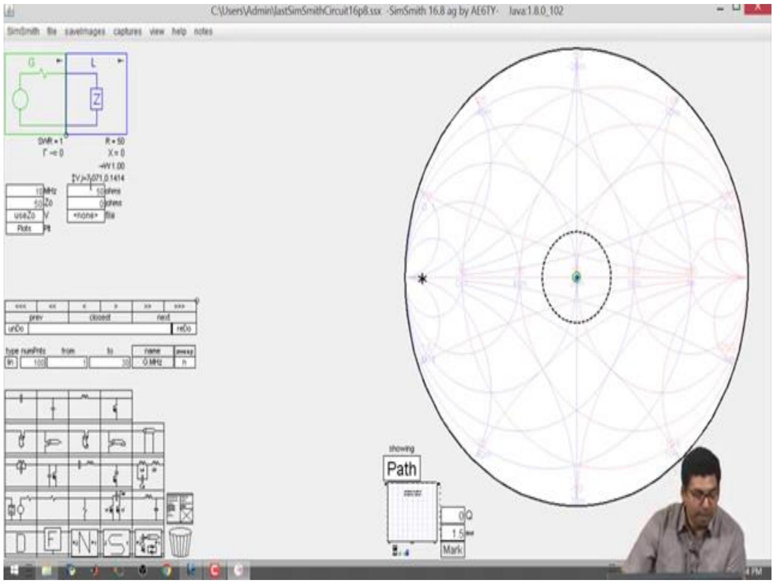

Now, we can start with a simple case and we can deliberately start with a we will start with a identical case matched impedance ok. On the right hand side, we have a Smith chart ok similar to what we have generated; constant resistance, constant conductance circles all right. Then, we have constant reactance and constant susceptance circles; all of them present in this Smith chart. And the center we are having the green and a blue dot ok.

The green part corresponds to the generating portion after the internal impedance that is you are looking in from this portion to the right side ok and the blue part corresponds to the load impedance ok. Since the load impedance is the 50 ohms, it is normalized with respect to the 50 ohms intrinsic of the generator ok and the result load impedance is equal to 1 ok. Now, you have to look for the intersections of resistance equals to 1 which is the circle passing through the center, reactance equals to 0; that means, you will mark the load resistance at the center that is what has happened over here ok.

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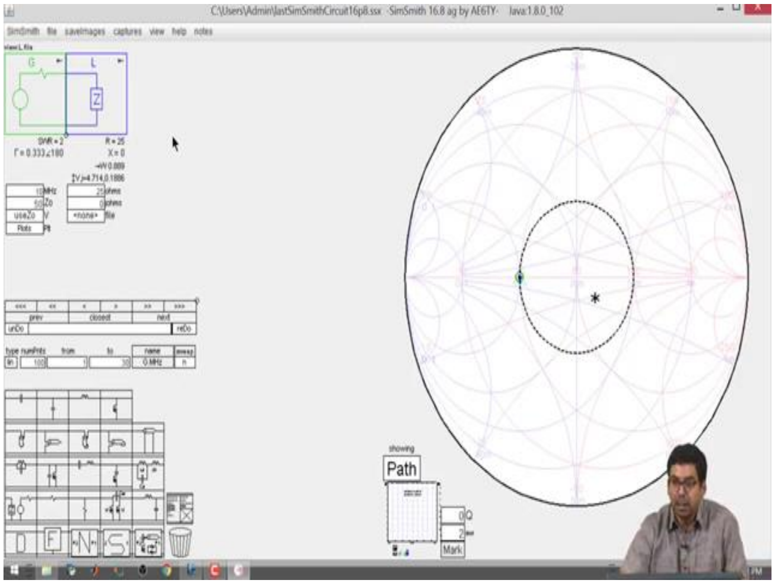

Now, we can make this slightly different say 25 ohms at the load. Now, we notice that the representation of the load impedance has moved to the left hand side of this Smith chart. In this Smith chart the normalizing resistance Z_0 that we are using is 50 ohms ok, which is the intrinsic impedance of the generator itself. So, with respect to this the load resistance is half, which means that you have navigated to the left of the Smith chart ok. So, your load impedance representation is over here ok and one can also look at the standing wave ratio is 2. So, can say that it is $\frac{25-50}{25+50}$ ok and you can find out that the standing wave ratio is going to be 2 ok.

So so, $\frac{25-50}{25+50}$ will give you γ ok, 1 minus; then you have to do $\frac{1+\Gamma}{1-\Gamma}$ to get the standing wave ratio and that is going to be equal to 2. So, I will just draw a standing wave, constant standing wave ratio circle. So, what has happened is in the Smith chart, if you draw a concentric circle with respect to the axis of γ plane right, you are going to be ending up with a circle that gives you constant voltage standing wave ratio. All along these points the magnitude of γ is identical. So, 1 plus mod γ divided by 1 minus mod γ is identical throughout this circle. So, if your load impedance is moving around this circle, your transmission, your circuit will experience the same standing wave ratio ok.

Now, once I have this the question that can be asked is how do I make the impedance as seen from the input side; generating side is over here all right, looking into this direction should be 50 ohms so that I do not get 0.889 watts as put over here, but I get the entire 1 watt. This is the objective of impedance matching all right. Now, the horizontal axis of this Smith chart over here also corresponds to reactance equals to 0 ok. So, a constant circle with infinite radius and reactance is equal to 0 ok. If the reactance is equal to 0, navigating along this circle all right, navigating along the x direction, if I keep changing the resistance I will go along that particular path.

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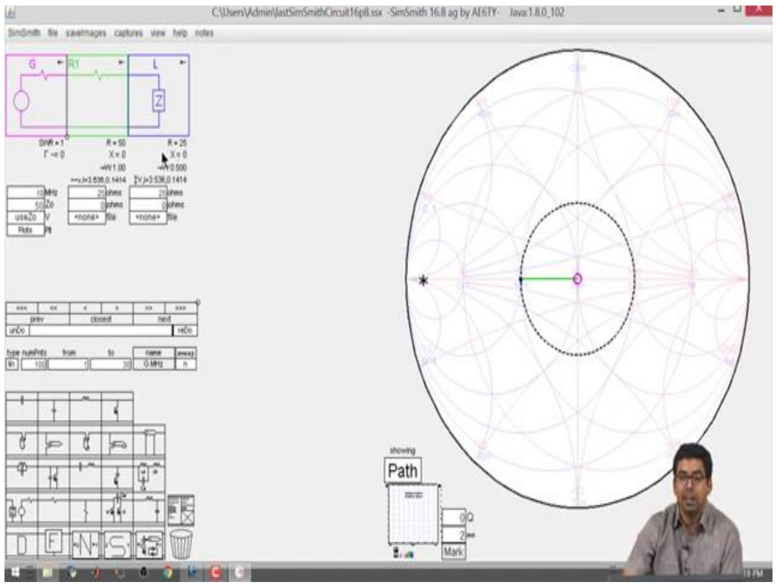

So, I can say that a solution to match the impedance can be simply to add a series to resistor in between like this and make the value of that resistor to be 25 ohms so that a combination of 25 and 25 will add up together to produce 50 ohms and when looked from the generating side, it looks like it is 50 ohms. So, the impedance matched all right. And you will immediately notice that the point in the Smith chart has moved to the center ok. So, the blue part is the load ok; normalized with the 50 ohms, which is why where it was originally before we added another resistance.

The resistance is the green part; this graph is very interactive. It shows that because you added a green color part, it moved from the load to this point as seen by the generator. Generator is pink in color corresponding to the pink color in the circuit. So, from the generator side, it sees that the circuit is fully impedance matched ok and it has no reflection coming to the generating side at all. So, the standing wave ratio seems 1, the reflection coefficient is 0. We have an impedance matched circuit clearly.

Unfortunately, while doing this impedance matching using a resistor, we moved along the constant reactance circle, we changed the resistor and we know that resistors will dissipate electrical power into heat power right. So, which means that incoming power over here was 1 watt as seen here, half the power has been dissipated here, only the remaining half is available for your load ok.

So, now the question becomes have you impedance matched and have you attained the objective? If the objective is not to have any standing waves or not have any reflection coefficient, you have done the job all right. However, by doing this we have actually worsened the amount of power that is available on the load ok.

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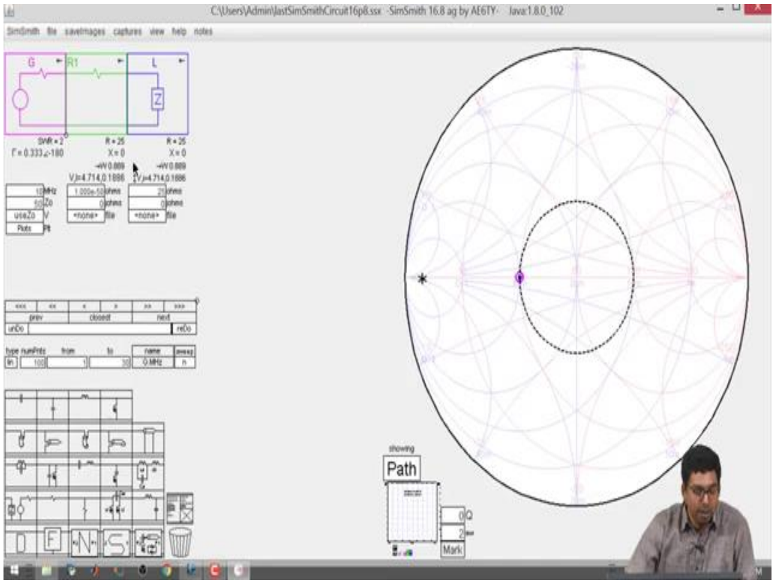

If I made this 0 should be short circuit ok.

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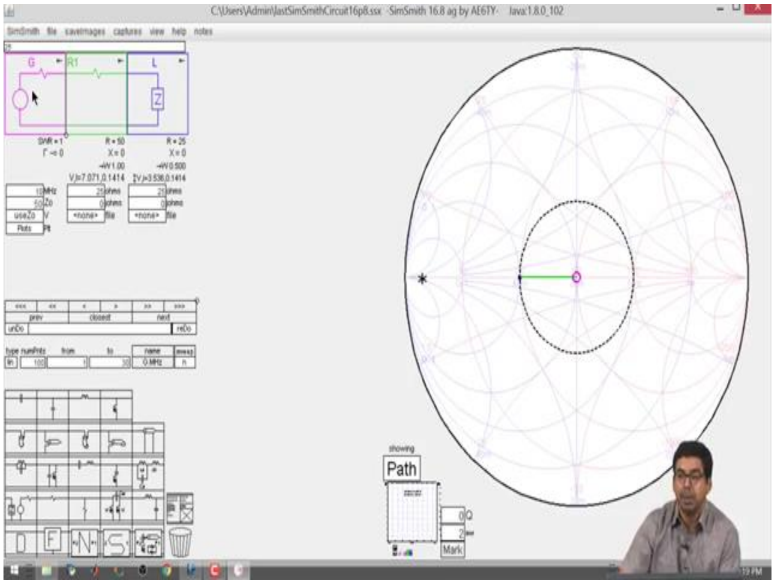

I actually had 0.889 watts being dissipated on the load and by going to impedance matched condition, I actually reduce the power that is dissipated on the load 2.5. So, the objective of impedance matching has to become very clear. It is not only to minimize the standing wave ratio or the reflection coefficient. It is to make sure that the rated power the maximum power that is possible is actually dissipated on the load right.

In this case, half the power is dissipated on the load right. So, what we are seeing is if we add a resistor in series, it is going to draw some power and under the impedance matched condition, it is going to dissipate some amount of power ok. Now, this particular example assumes that your load resistance is less than the intrinsic impedance of the resistor. So, you could add a series resistor right. So, let us go ahead. Remove this part again. Will make our load resistor higher ok.

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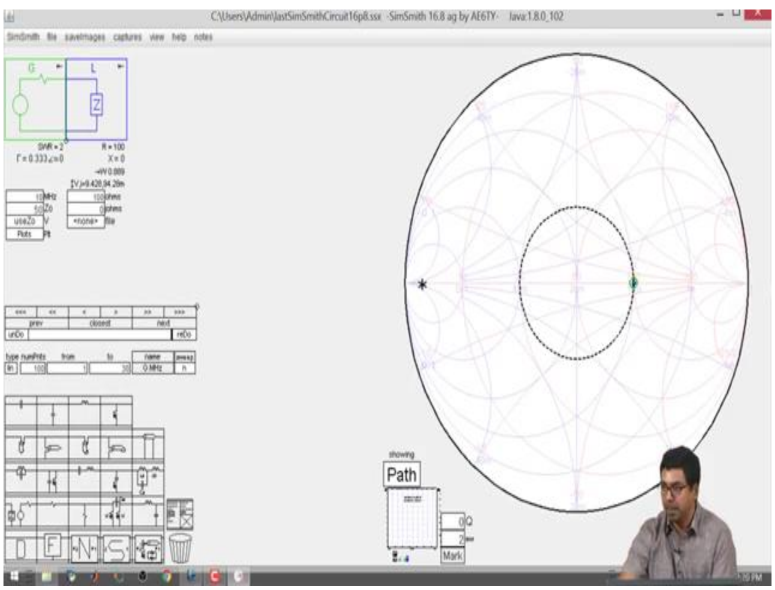

So, we will make it double; previously we had a half, now we will make it double ok. Load resistance is double ok. So, the load resistance normalized with respect to the intrinsic impedance of the generator 50 is 2 ok. So, you have to look for the circle where r is equal to 2; r equals to 0 is the outside circle; r equal to 1 is the circle that passes through the center of the Smith chart; r equal to 2 is the next circle that is following it. Reactance is equal to 0 that means, the horizontal axis is the intersection.

So, this is your representation of load impedance on the Smith chart ok. It is present over here. Now, I cannot add a series resistance to match the impedance because a series impedance will only move this to the right hand side, more and more ok. So, I need to add a resistance, but maybe I have to add it in shunt ok. I have to add in shunt ok.

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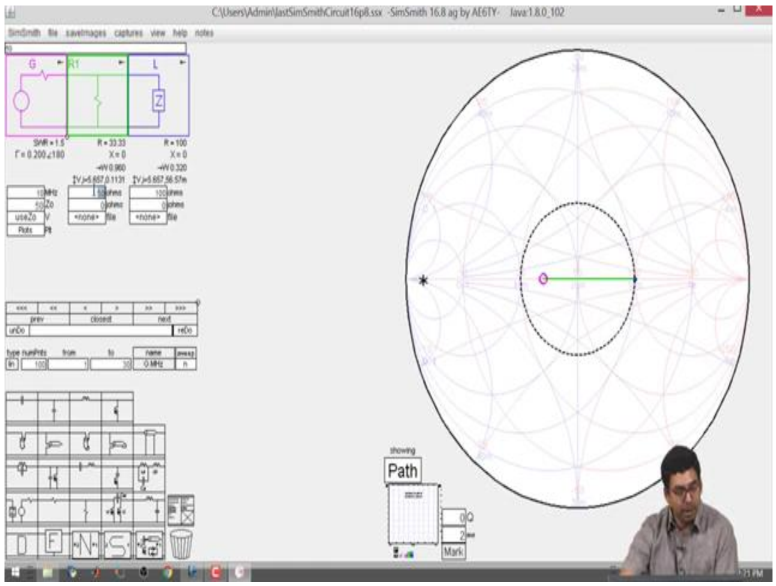

If I added it in the shunt all right and if I kept on increasing this value, if the resistance in the shunt path approaches infinity, that particular arm will become an open circuit ok.

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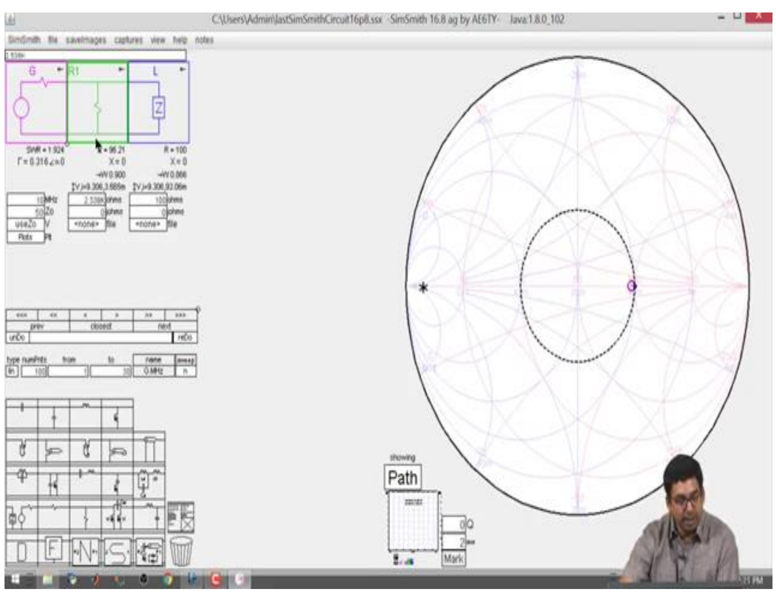

So, the entire current will flow only through the load and you will not be moving the resistance seen by the generator part. So, you need to know the, you need to adjust the values of and as you start reducing the amount of shunt ok, it will go all the way to the left hand side of your Smith chart ok.

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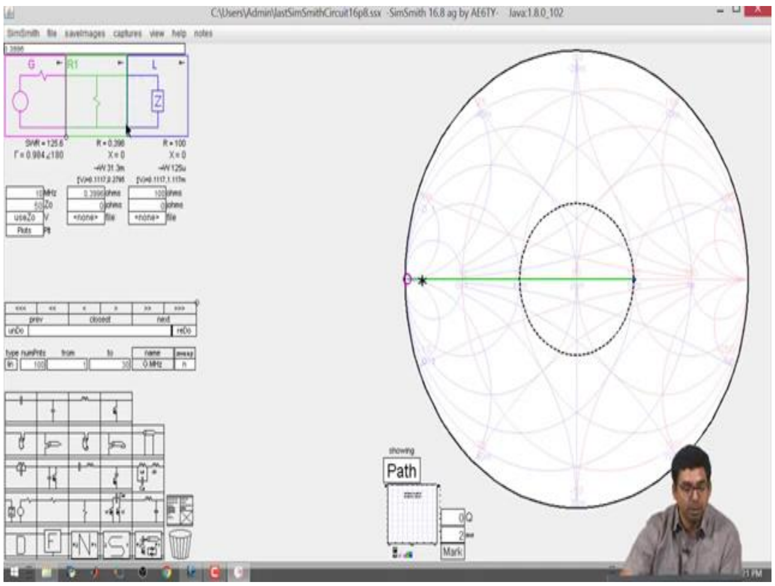

If the conductive path here is having negligible resistance, almost no current will flow through the load ok; that means, that you would have short circuited and the representation that is seen by the generating side here is a parallel combination of a short circuit and the load, which is short circuit. So, the reflection coefficient goes to minus 1 ok. So, in order to match it, I need to find the correct value of resistance to put. So, I keep increasing the value of resistance till I reach the center of the Smith chart ok ok.

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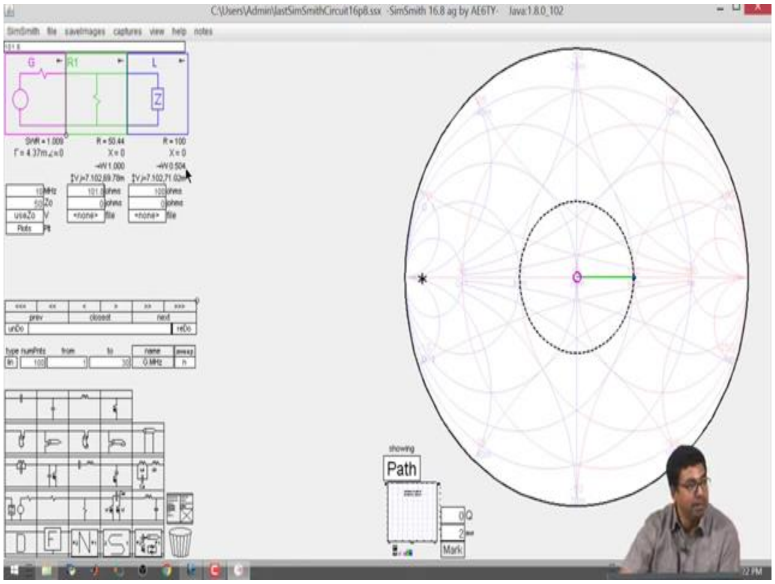

Somewhere about that. If you see the reflection coefficient is 4.37 milli, the standing wave ratio is 1.009 and the power once again is 0.50 watts ok. So, if I zoom in and if I make even more corrections. So, this 100.8.

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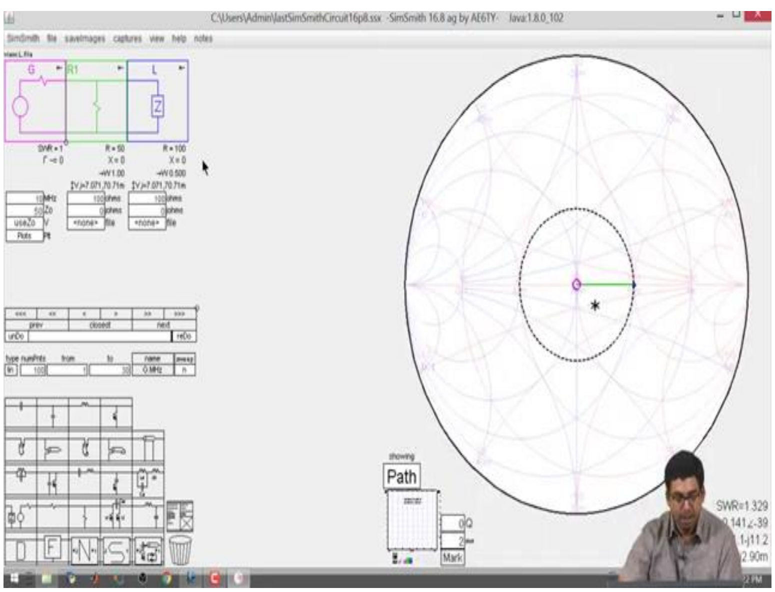

So, I make it 100 ohms because 100 ohms in a 100 ohms in parallel will become 50 ohms; one-half ok. So, I will make that ok. So, now, what happens is the circuit is impedance matched, standing wave ratio is only 1, reflection coefficient is 0; but I still have only 0.5 watts at the load ok. So, once again by adding a resistor you moved in a line of constant reactance, this case the reactance is 0. So, you moved, but adding a resistor comes with a penalty in terms of power that you can get at the load end ok. So, now the question can be can we take a purely resistive load and make it appear at the center of the Smith chart as seen by the generator, but have all the power dissipated at the load ok.

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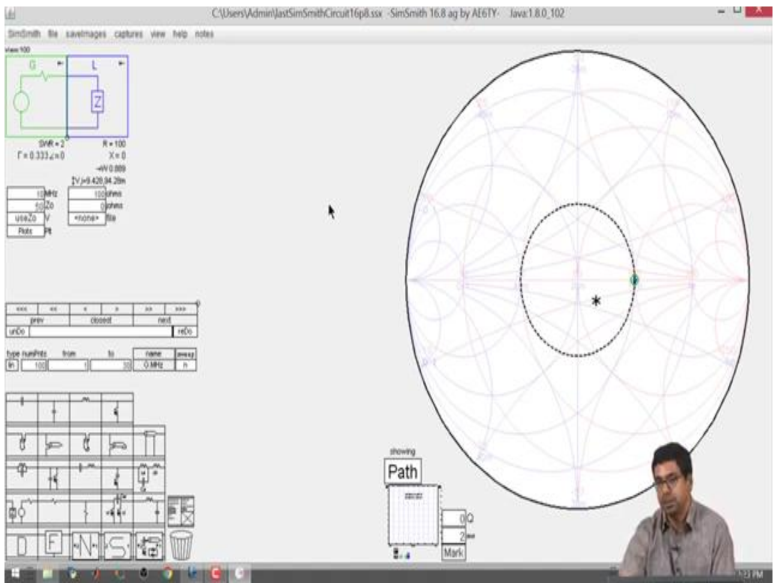

So, this means that we cannot use resistors. Then, we are left with two other options ok. We can either do so, so I will go back to 25 ohms ok. We can do two things, we can add say inductors and capacitors and try to understand the meaning of the two ok. So, the first thing I will do is try to add a series capacitance ok.

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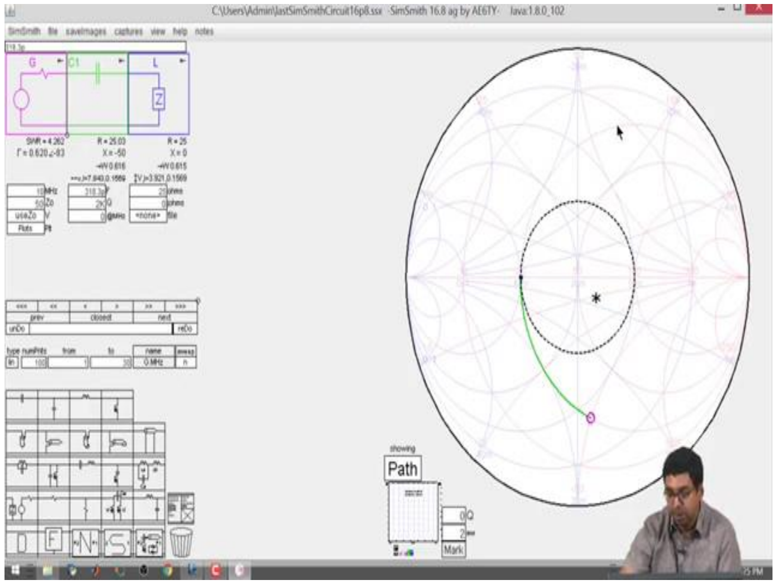

So, this is the load representation on the Smith chart. Once you add the capacitance, the capacitance moves the load as seen by the generator in the negative direction. Because it is $-jX_c$ right. So, it is going to move it to the negative direction and your reflection coefficient is going to change. So, this is the impedance as seen by the generator. This is going to be your load impedance actually before adding the capacitor. So, the green part is the capacitor, it moves it along this side and the generator sees this part ok. Now, I understand that if I keep on changing the value of the capacitance all right, I am increasing the value of capacitance to be very very large.

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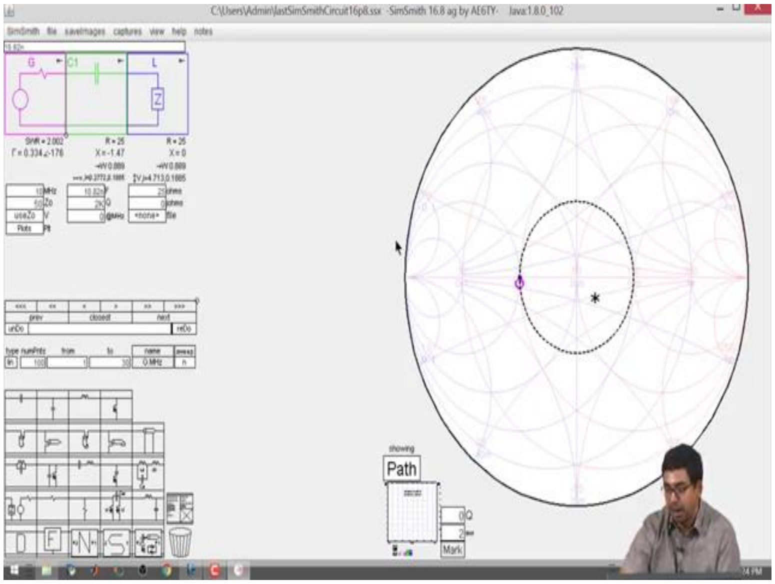

If the capacitance becomes very large over here right, you are approaching the reactance part to be approaching to infinity right, a no, the capacitance is very large, then you are making it actually a short circuit all right so that means, you will see the effect of only the load and so, the point converges to the original load impedance. So, again, we can make a change to decrease the capacitance ok. It traverses along the point of constant resistance ok 25 ohms corresponds to r equal to 2 all right and you are changing the capacitance; it sweeps the same place in the I mean same circle and reaches all the way to the right hand side point ok.

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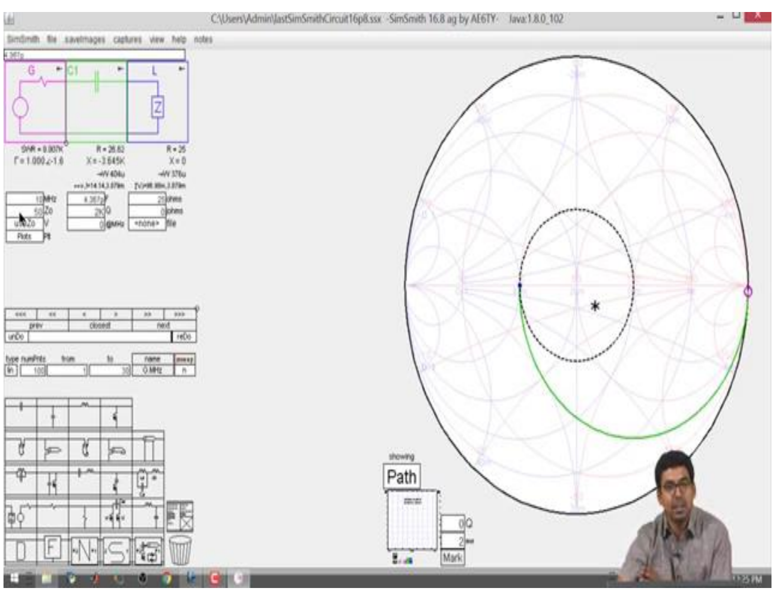

So, adding a series capacitance, you can do some level of thing. You go in the half plane below and you go along a constant resistance path ok.

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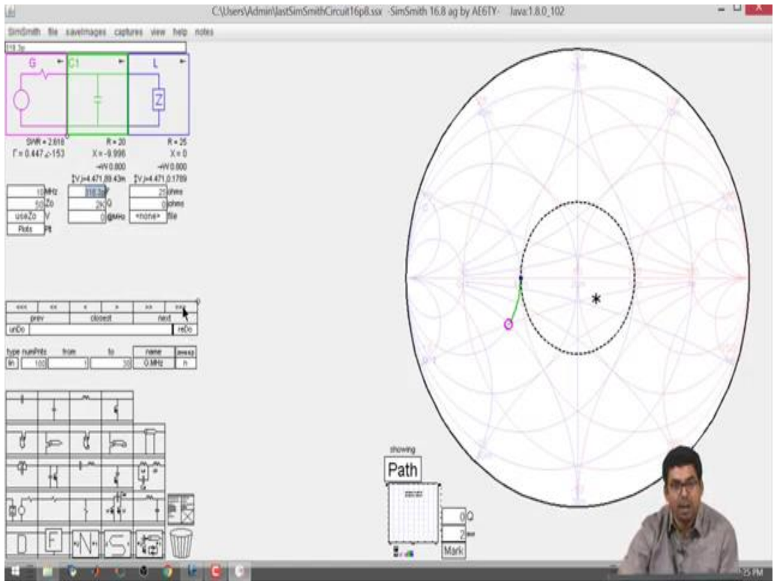

Another thing that one can do is they can add a capacitance in parallel instead of series right. Once you add in parallel, you will be able to go along a constant conductance path ok. So, we keep going this way, the negative half you will reach the other side.

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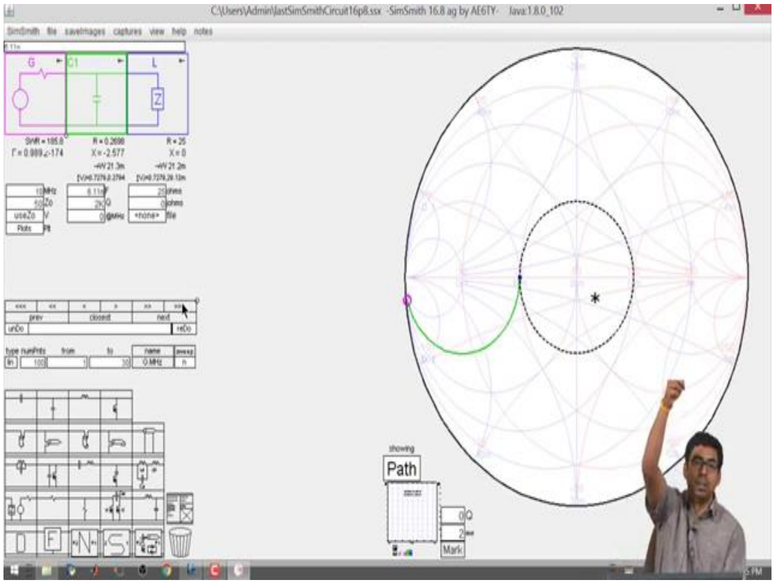

So, with a capacitor, you will be able to go either this way or you will go this way depending on whether you connect it in series or in shunt ok. Now, in order to reach the point in the middle one of the most important things is you we have to come from the load, we have to say come down if you are going to add a parallel or a series capacitor, you will coming down on the negative half plane and you will have to intersect one of the circles which goes through a the middle of the Smith chart.

The goal is always to come to the middle of the Smith chart and there are two circles, which are intersecting corresponding to r equal to 0 or g equal to 0. Both of them pass through the center of the Smith chart. On top of that, x also is equal to zero, the horizontal axis ok. So, you have to arrive here. So, you have to reach one of these two points and arrive at x equals 0, this is going to be the objective.

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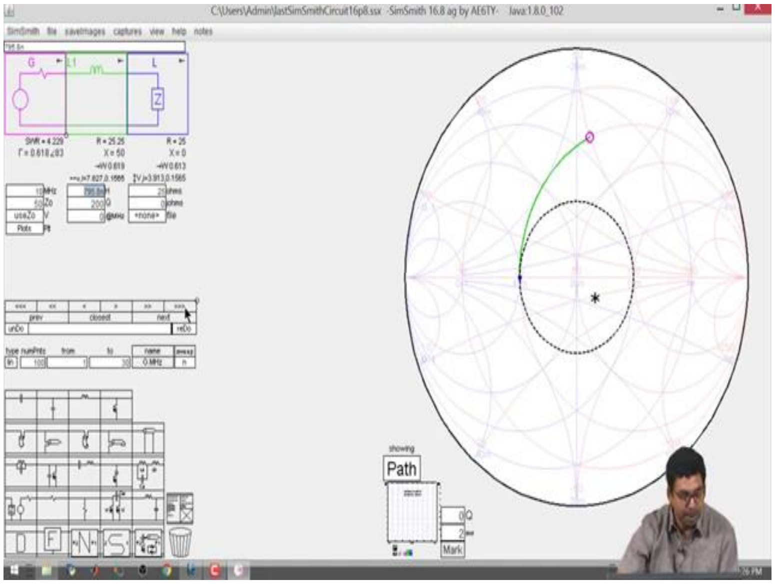

So, we can also see what the inductor does. A series inductor will move the point to the top half plane. As you keep increasing the inductor, inductance value keeps going towards the right hand side all right as seen by the generator and if you make this a parallel inductor right ok, you can go to the left hand side.

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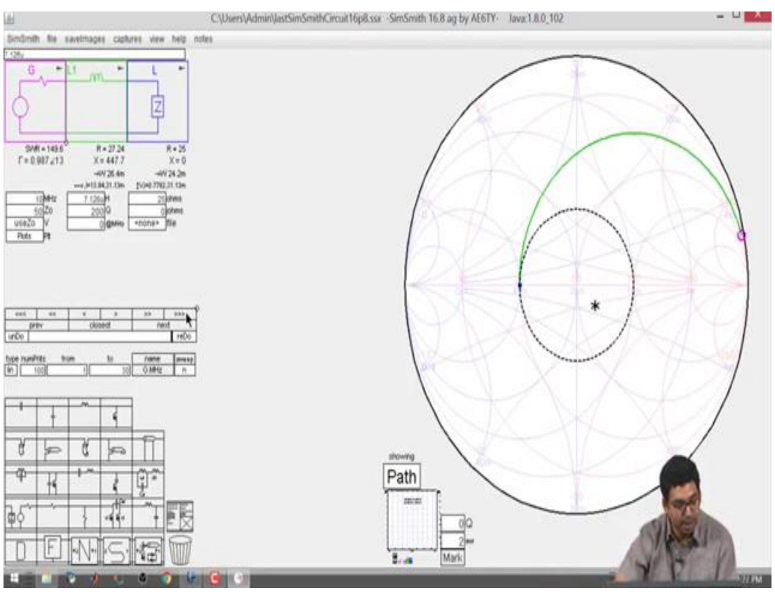

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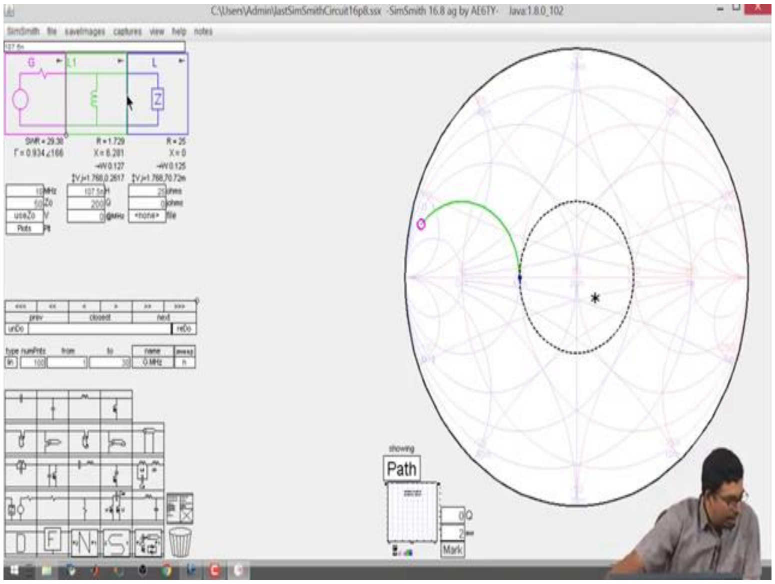

So, these are the combinations possible, one can go ahead and try to do the impedance matching without using a resistor ok, and we can see the consequence. Now, what we will do is we are having a parallel inductor already moving in this direction all right and we can always connect a series capacitance ok; we could do that.

So, the green part here is the capacitance connected to the load side ok and this pink part is corresponding to the inductance that you have connected over here and if you are able to adjust the 2 parameters, you will be able to arrive at the center ok. So, what we can do is we can start manipulating things all right.

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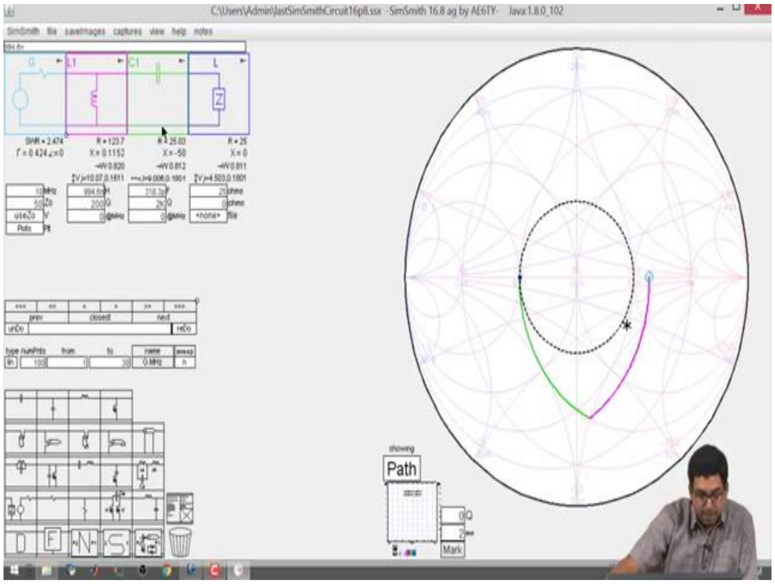

So, I can start increasing the inductance to reach the horizontal axis, then again go to the capacitance part and manipulate the capacitance right to see how I can traverse.

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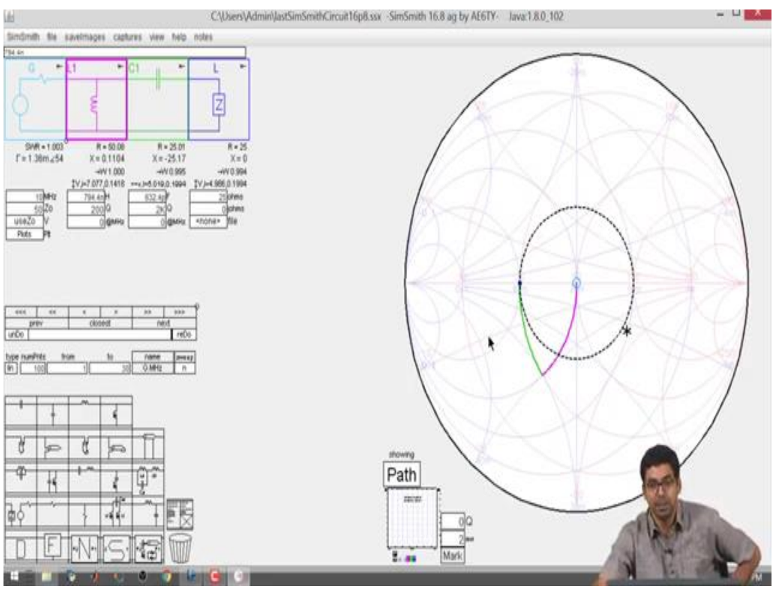

Here, we go. It approximately can zoom in and do a fine to unique. So, one of the things we notice here is the load was present here is the blue ok to the load we have connected a series capacitor which pushes it to the negative half ok and it comes and it actually intersects G equal to 1 circle first ok. You are hitting the G equal to 1 circle, once you have done that we are adding an inductor to go above and then you are hitting this a Smith center of the Smith chart, where the reflection coefficient is equal to 0 all right.

And if you check the power that is available at the load since L and C do not consume any power, you are having 1 watt, which is the rated power of the generator appearing across the load ok. Now, this is not the only way, you could also do this in multiple ways. For example, no you could always have. So, let us say it could have a capacitor and an inductor like this all right.

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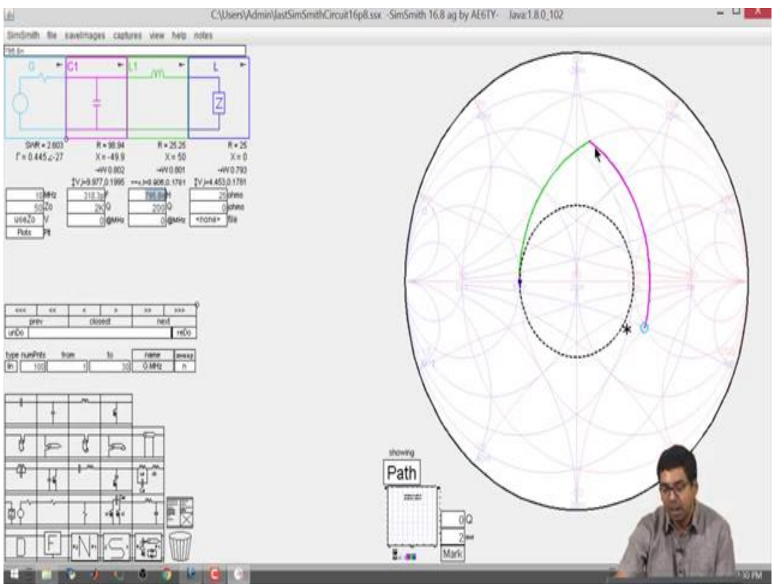

So, previously, we had a capacitor connected to the load in parallel, it could always replace that with the series inductor all right. So, the first point where you will before you are travelling down step downward hitting the G equals to 1 curve, but since you have connected an inductor will be travelling upwards and the goal can be to meet this circle once again and then, travels down to the center ok. So, we can adjust the value of the inductor ok. So, instantly with some minor adjustments to the capacitor, I will be able to get a standing wave ratio of about to 1 all right.

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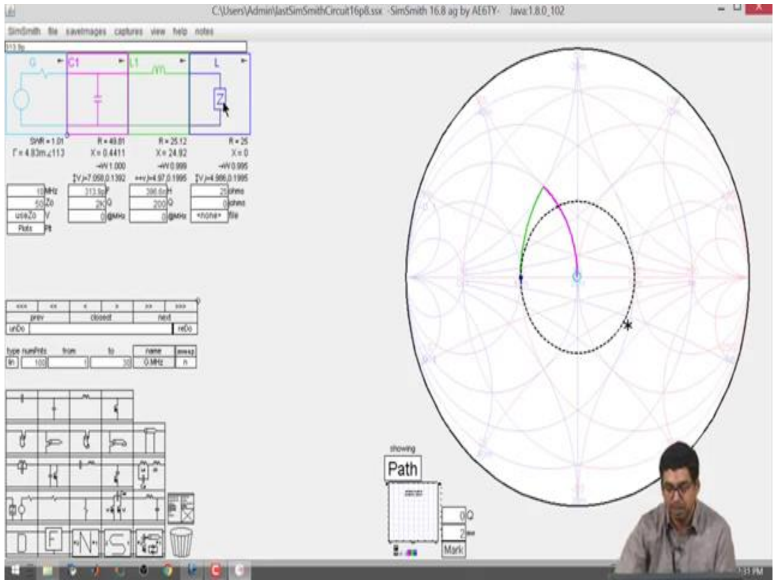

And the power that is available on the load is about 1 ok. I can do it very precisely, but I am not able to do it with the mouse over here ok. So, this is operating at 10 megahertz, one can always go ahead and calculate the reactance for these frequencies and then, they can see what is the value of inductive and the capacitive reactance and how they cancel out each other ok. This is the most elementary way of doing some impedance matching ok. Now, we notice that the resistance will move you along the path of the circle of constant reactance, if your load is purely resistive all right. Then, adding any series or shunt resistance will move only in the horizontal axis of your Smith chart.

If your load is complex and if it is somewhere else and if you add resistance simply go in the along the circle of constant reactance ok. So, adding a resistor is actually going to come with some penalty because you are going to lose some power, but adding an L and C will not give you that penalty and it will dissipate all the power at the load. This is the most elementary way of doing impedance matching in a circuit. Again now, we have to understand what will happen with a transmission line ok and then, I will introduce the transmission line between the source and the load all right and there are some parameters for the transmission line that I am going to change.

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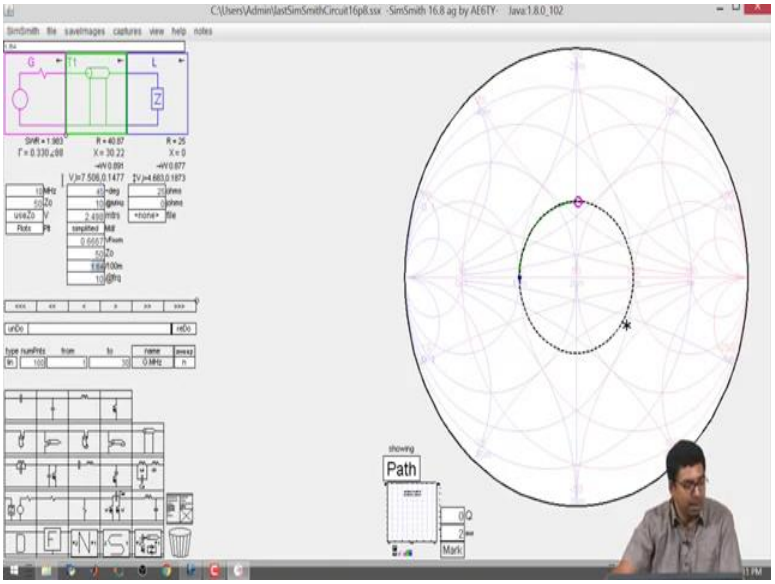

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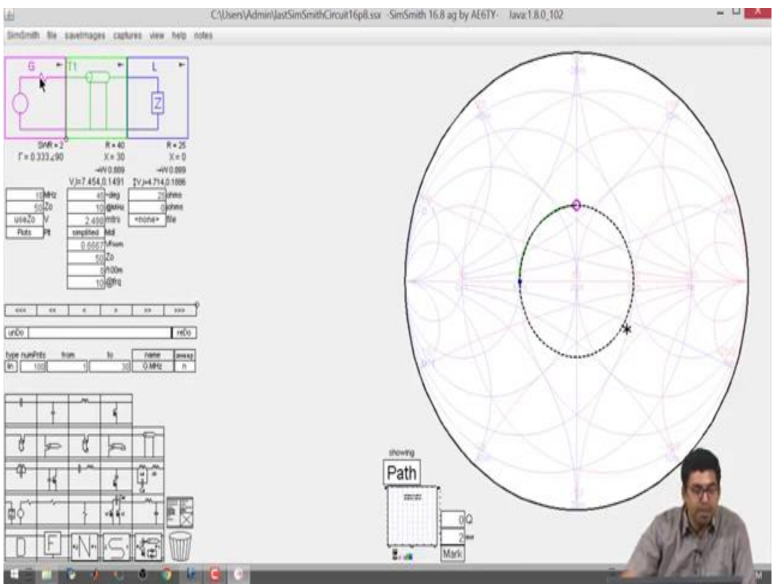

First of all, I am going to make the loss less transmission line ok and I am going to keep the transmission line characteristic impedance to be matched to the generator ok. Most of the time generators have some ratings, they are operating at some frequency and they are supposed to have some termination. Here, we are assuming a 50 ohm intrinsic impedance for the generator. Transmission lines widely available for 50 ohms or 75 ohms. In this case, we are choosing a 50 ohms transmission line cable. It is a 50 ohms standard cable. The load is what we are trying to match ok. The load can be something else ok.

So, here there are a few things that we are noticing ok. It says that 0.667 velocity factor; velocity factor means that the speed at which the waves are going to be travelling in this transmission line with respect to the speed of light in vacuum. So, assuming that the speed of light and vacuum is $3 * 10^8\ m/s$ ok; 0.667 means that the velocity will be $2 * 10^8\ m/s$.

So, in this transmission line $1/\sqrt{LC}$, will correspond to $2 * 10^8\ m/s$ ok which is almost a practical, I mean that is how that is the velocity of a signal in a transmission line. Now, one of the things that we have noticed is the load is present here connected to a transmission line, the transmission line moves the impedance point from the axis over here to 90 degrees above like this. The angle of phase that the transmission line is providing is only 45 degrees ok.

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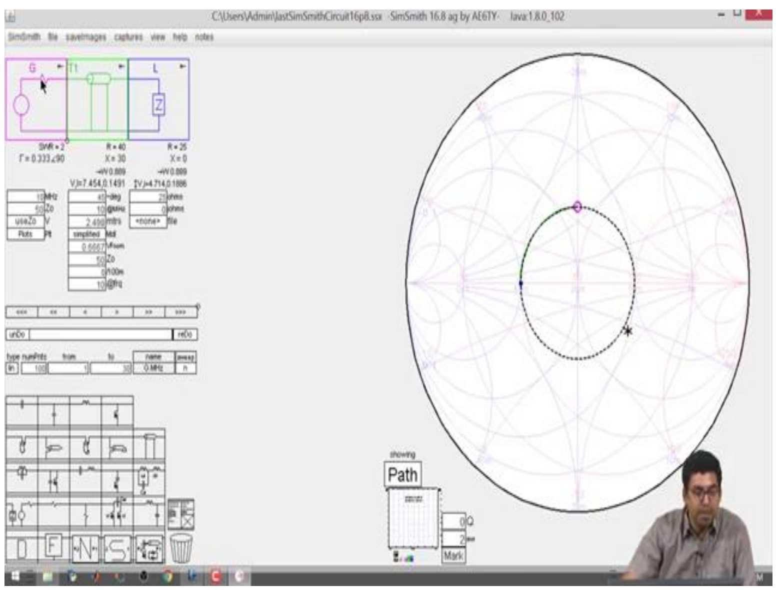

So, the transmission line is providing only 45 degrees phase, but it is moving the impedance the same all right by I mean the angle of your reflection coefficient is going by 90 degrees all right. It is simply because we know the formula for the reflection coefficient it has $\Upsilon_L e^{j\beta l}$. So, βl if it changes 45 degrees, the angle of the reflection coefficient will change twice of that. So, for that reason all right, there can be some confusion when you are reading this Smith chart. If you travel around the Smith chart, ok all right. So, if I go for 90 degrees to be the phase provided by the transmission line, I will reach the diametrically opposite point in the reflection coefficient; 180 degrees change ok.

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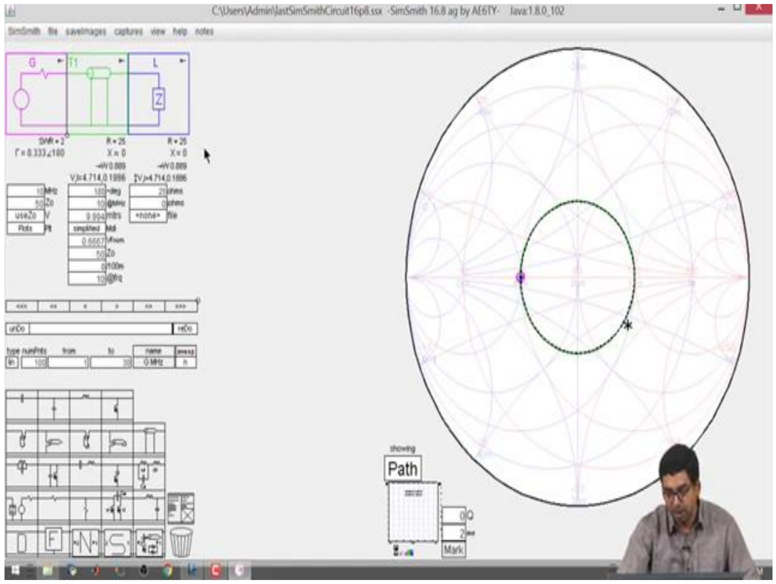

So, the entire Smith chart can be traveled with 180 degree phase shift of your transmission line, it forms an entire full circle ok. So, this is one thing that we have to register in our minds. The second thing is now we have gone over the transmission line all right and we have provided an 180 degree phase shift to the signal, but you have reached the same point on the Smith chart ok. 180 degrees corresponds to $\lambda/2$ ok which means that in a transmission line as the length changes, the impedance will repeat itself after every 180 degrees or $\lambda/2$ ok which is consistent with what we had seen before ok.

So, we had short circuit and open circuit bound I mean termination for the transmission line and we saw that at every $\lambda/2$ there will be a 0 crossing in your impedance in the length of the transmission line. So, every lambda over 2, the transmission line parameters will again start to match in a lossless case ok. So, the actual length of the transmission line really does not matter, only the electrical length matters. Electrical length is βl; β is your phase constant multiplied by l.

So, it has to sweep a 2π. So, a transmission line does something very different from L and C individually all right. It has a tendency to move around the circle of constant VSWR. Previously, we were either moving in a constant circle of a resistance, conductance, reactance or sum substance. A transmission line will move along the circle of constant VSWR, it means that whatever be the length of transmission line that you are going to be choosing ok, the VSWR seen the transmission line is going to be the same ok.

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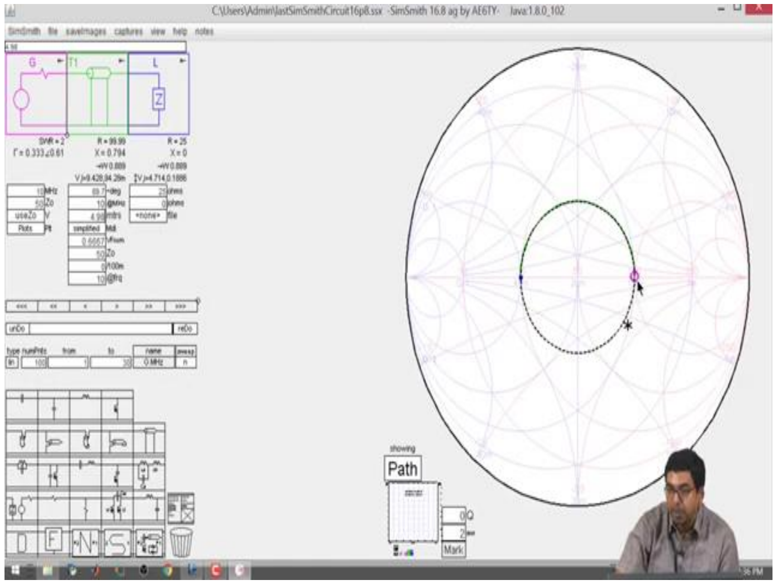

But the impedance that is seen could be different, the length depending on the length of the transmission line. So, if you have length like this, your generator will be seeing an impedance at this point all right instead of your load impedance is here, but the generator sees the diametrically opposite impedance connected to it right.

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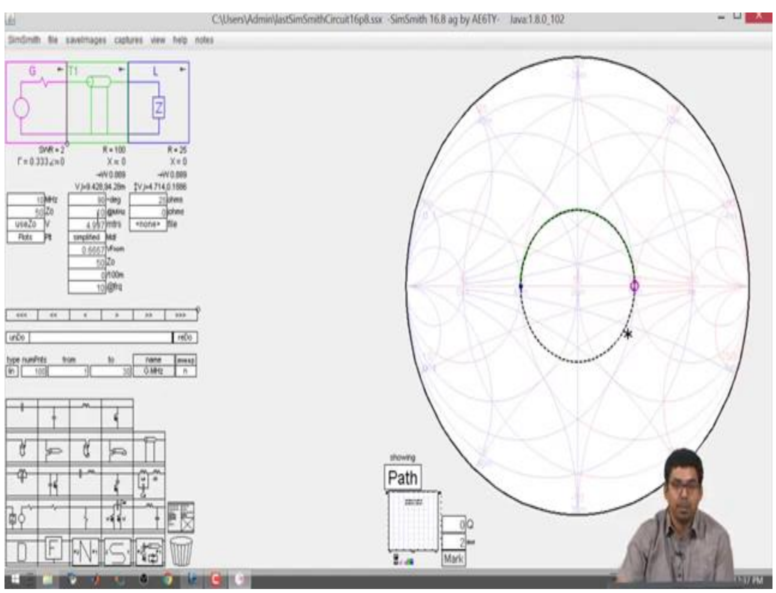

So, as you know one of the things we see is for a purely resistive load ok in order to reach the intersection with the same line again all right. So, here it is a purely resistive load x is equal to 0 and if I use a transmission line just with 90 degree phase shift ok; 90 degree phase shift, I reach the horizontal axis again all right. Now, I would like to bring this load as seen by the generator to the center of the Smith chart. I cannot adjust the length any more, I will have to adjust some other parameters ok.

Some other parameters can be the characteristic impedance of a transmission line itself. So, I can start saying increasing and seeing what happens. So, it goes further away. So, that is not the correct direction and I can start decreasing the characteristic impedance and I will notice that it stays on the line. I mean it stays on the horizontal line, but it keeps going towards the center of the Smith chart ok. Now, I have matched ok.

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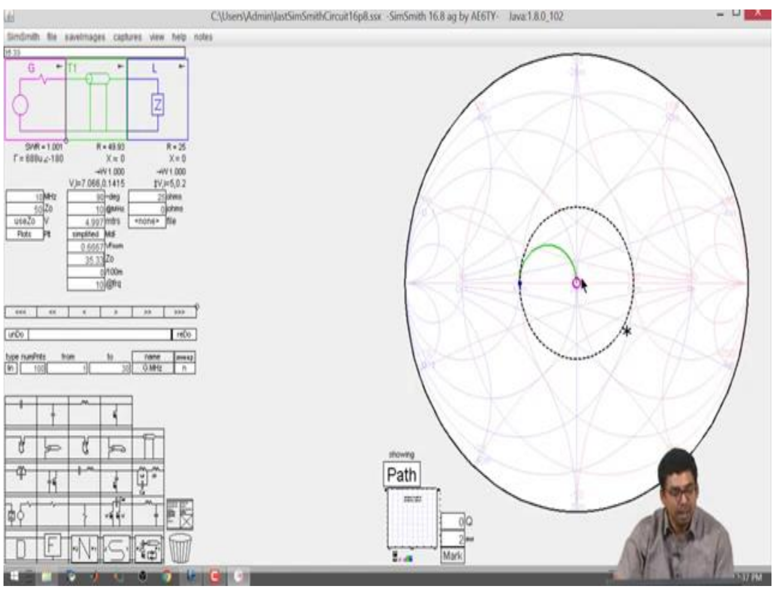

So, I am noticing that the power available to the load is once again 1 watt ok and I am providing a 90 degrees phase shift. So, this is a lambda over 4 length transmission line cable. It is quarter wave length cable and if it is characteristic impedance is 35.3 ok. I am getting an impedance match as seen by the generator ok. We can make a quick calculation for this.

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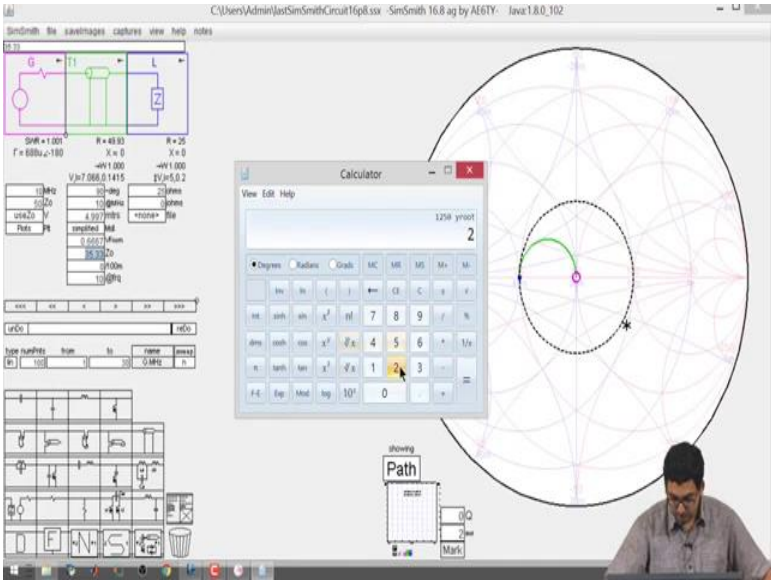

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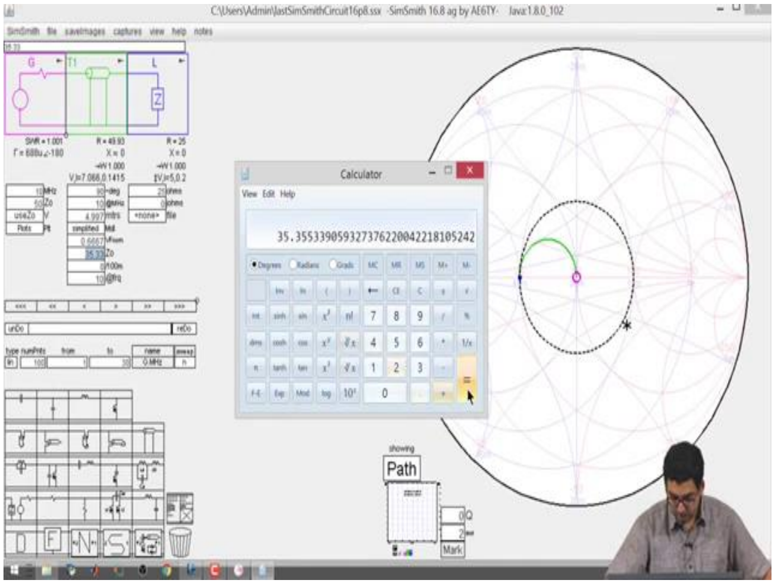

We can take the impedance which we are using for normalizing or the intrinsic impedance of the generator which is 50 ohms ok and we can take the load that we are trying to match which is 25 ohms ok and take a square root of this. Wow, ok that is 35.3553 ok; 35.3553. So, I am close to 35.33 ok.

So, it seems that there is a relationship between the characteristic impedance of the cable that you have to use and the product of the characteristic or the intrinsic impedance of the generator and the load. So, the relationship that seems to be a seems to be followed ok is Z matching for the transmission line seems to be

$$Z_{matching} = \sqrt{Z_g * Z_L}$$

This is what seems to be happening ok.

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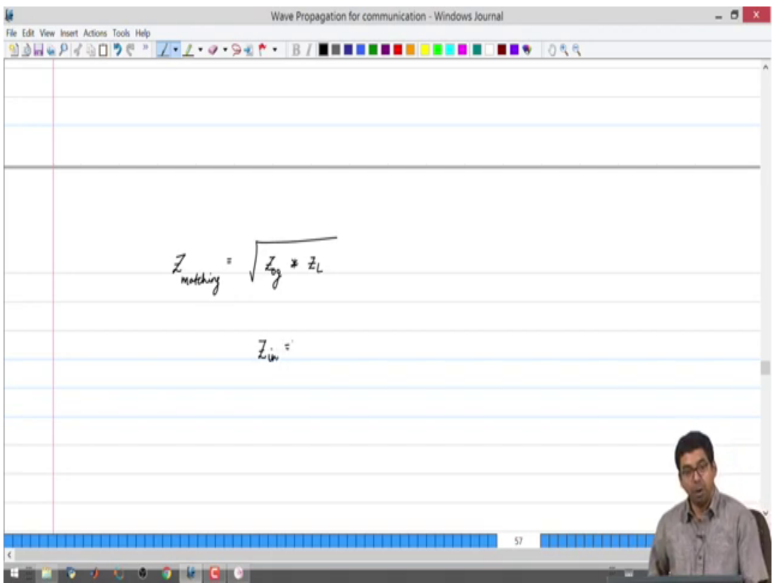

And this can be easily proven. You can take your equation for Z in that we had written before all right. So, we had written the equation for Z in ok.

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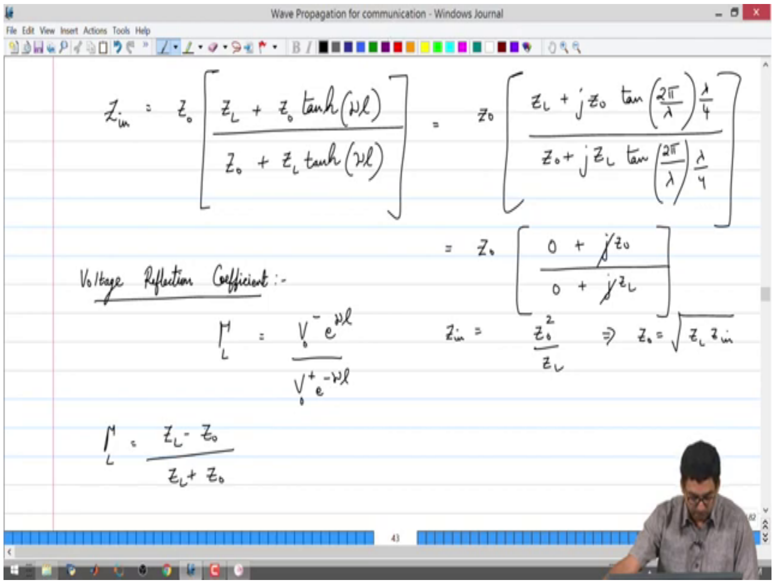

So, you have

$$z_{in} = z_0 \left[\frac{z_L + z_0 \, tanh \, tanh \, (\gamma l)}{z_0 + z_L \, tanh \, tanh \, (\gamma l)} \right]$$

This is for a lossy transmission line circuit. For a lossless transmission circuit, you will remove the hyperbolic part all right and instead of γ, you will simply write this is βl, ok.

Now, βl in this case corresponds to the electrical length that you are using $\beta = \frac{2\pi}{\lambda}$.

So, I will make some simple substitution. So, this is

$$z_{in} = z_0 \left[\frac{z_L + jz_0 \, tan \, tan \, \left(\frac{2\pi}{\lambda}\right) \frac{\lambda}{4}}{z_0 + jz_L \, tan \, tan \, \left(\frac{2\pi}{\lambda}\right) \frac{\lambda}{4}} \right]$$

$$= z_0 \left[\frac{0 + jz_0}{0 + jz_L} \right] = \frac{z_0^2}{z_L}$$

$$z_0 = \sqrt{z_L z_{in}}$$

In our case Z in is nothing but the impedances seen by a generator ok. So, it seems to be following the geometric mean ok. So, which is what we have arrived at using a Smith chart ok.

So, the approach that we have taken is that of a quarter wavelength transformer. This is commonly known as quarter wavelength transformer, I will go back to this diagram you will have a 90 degree phase producing transmission line of a characteristic impedance which is the geometric mean of this a input impedance here and your load impedance and then, that is going to produce a impedance matching. Remember that we have taken the loss less condition, so we are starting with the horizontal axis and ending at the horizontal axis also ok. So, this is a straightforward case. But what are the merits and demerits? Merit is ok. It provides me with all power at the load. The demerit is it is not easy for you to go and buy a cable for which has a 35.33 ohms characteristic impedance.

So, it is good to understand that it can be done, but a practical approach is just connecting L and C at your load and actually trying to match what is going to happen ok. Are there any other ways to do this? Yes, there are multiple ways of doing this, but before going there, let us also see some more details ok as to what the cases can be ok. So, first what I am going to do is for now I have assumed the load to be real ok, I am just going to make this load to be having a real and an imaginary part and then, I am going to walk backwards what are all I can do.

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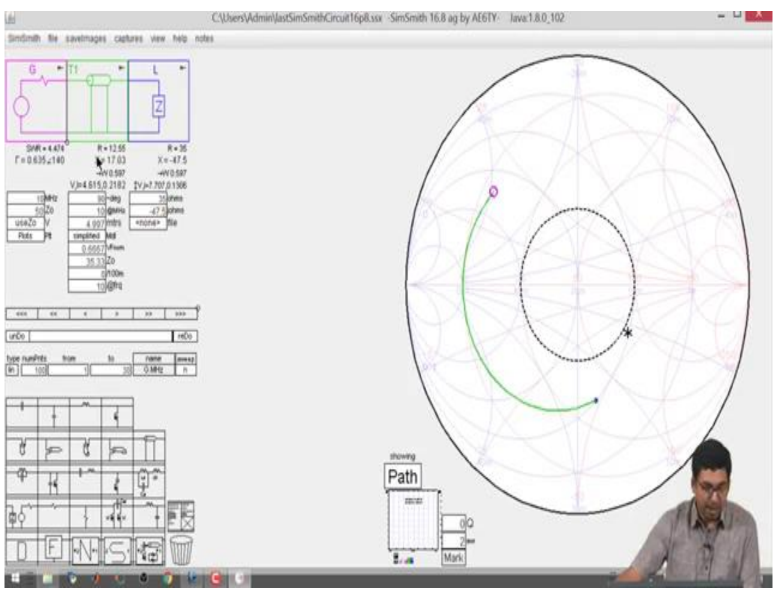

So, I am going to be taking a load which is say 35 minus j 47.5 and I am going to get rid of the transmission line first.

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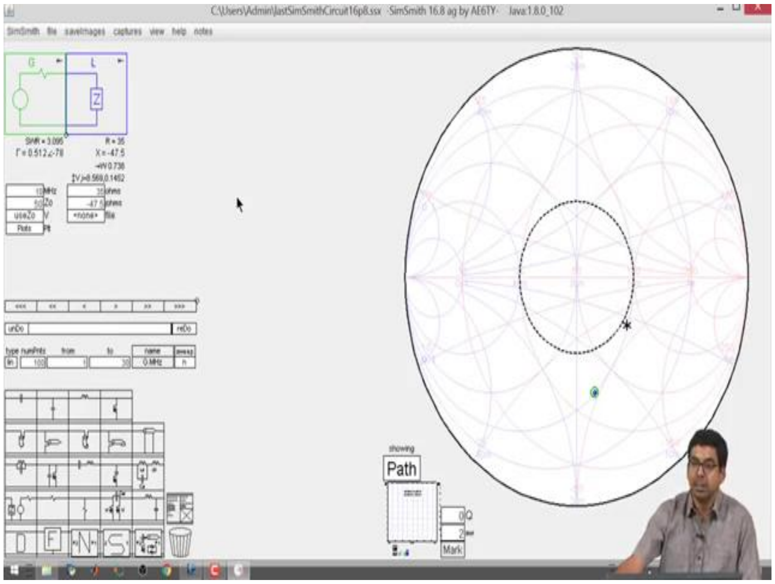

I am going to start with a conventional approach and then, the transmission line based approach ok. Now the load impedance is not on the horizontal axis ok. It is not on the horizontal axis; that means, it is clear that you have to do some reactance manipulation also ok. You will need to add some passive components and you will have to add some reactive components. The resistor will get you along the circle all right. But you will still need to get here; going up the tra I mean here means sum you know L and C ok. So, what we could do is we could start with say a series capacitor. So, we put some parallel inductors and see what happens right.

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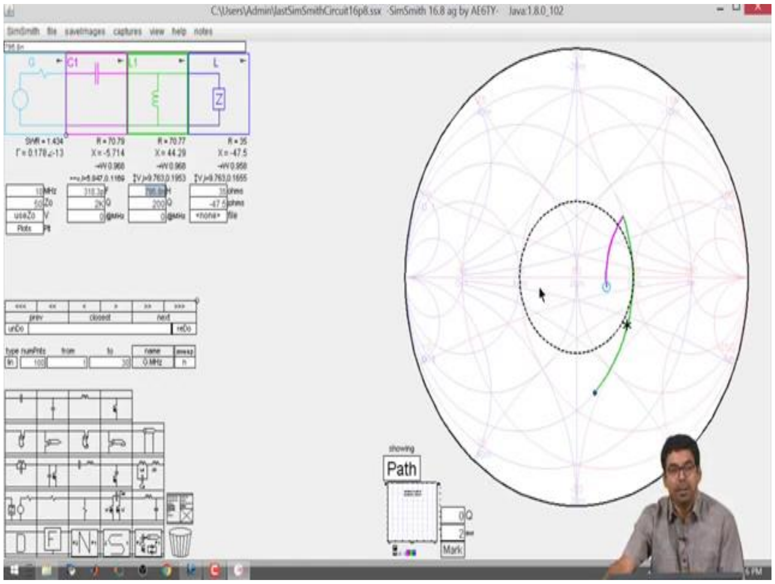

This is the load, adding the inductor in parallel moved along the conductance circle upwards and adding the capacitor in series made you go along the constant resistance circle downwards ok. This was not intentional, I just plugged in and it seems to happen, but since it is happening, I am going to manipulate it all right. So, I am going to start with just playing with the inductance values, I already matched ok.

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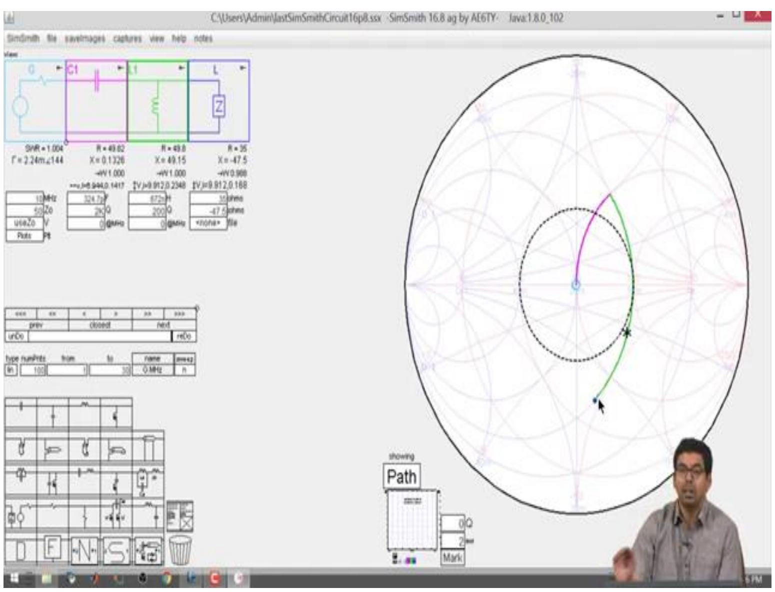

Its close standing wave ratio is 1.004 and assume it to be 1; reflection coefficient is 2.24 milli, it is almost no reflection and the power available at the load is 0.988, you can take this to be 1 watt. I have matched a load which is not resistive using only L and C ok. This is one way of doing it all right. You could also think of doing this in other ways all right. The other way is one of them will involve a simple transmission line approach ok. So, I am going to remove these two components ok.

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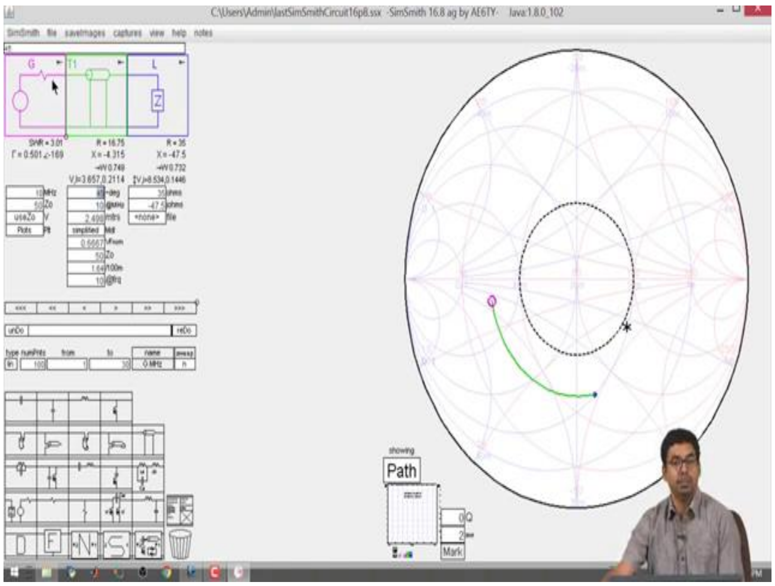

Now, I know that I can impedance match with a L and C, there is no issue. Now, I want to understand what the transmission line will do over here all right. Remember that just like your generator the transmission line has a characteristic impedance of 50 ohms ok, which is practically procurable right. But let us say that since we have done quarter wave length matching before for a purely resistive load, what happens when the load is complex; is it possible to still match with the transmission line? This is the question ok.

Let us have a look at it first and then see whether it is possible to match or not. All I am going to do is I am going to change the length and I am going to change the value of Z to see whether I am able to arrive at the center of this Smith chart ok. So, I am going to do this ok, I am getting away from the center. So, I am going to go the other way and see how close to the center, I can get with this ok. I am able to get towards the center, but I am not able to go down all right.

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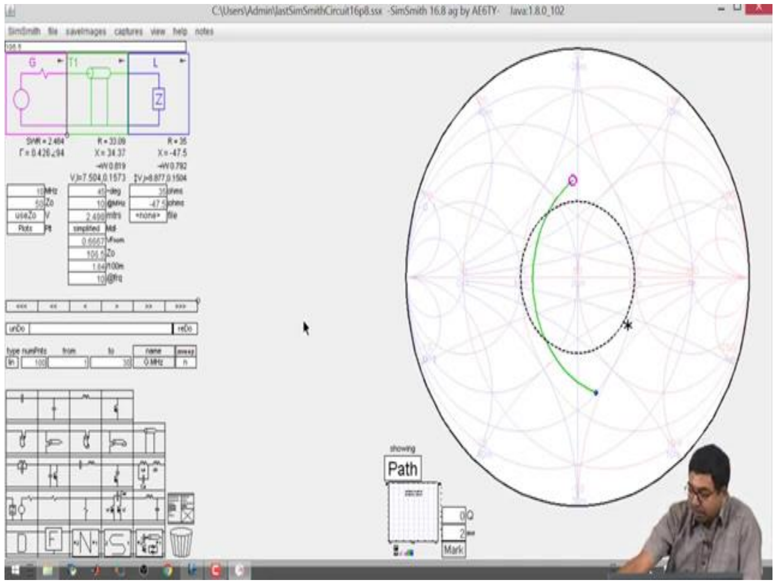

To go down, I know that I will see what happens ok, getting there right ok.

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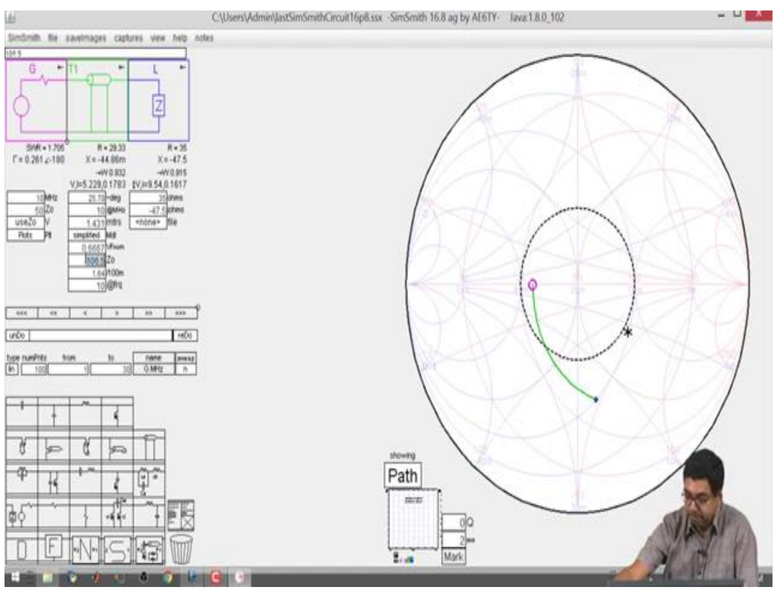

Some manipulation; clearly looks like it is not going to be easy to do this. It is not going to be easy to do this, that is what I am saying all right.

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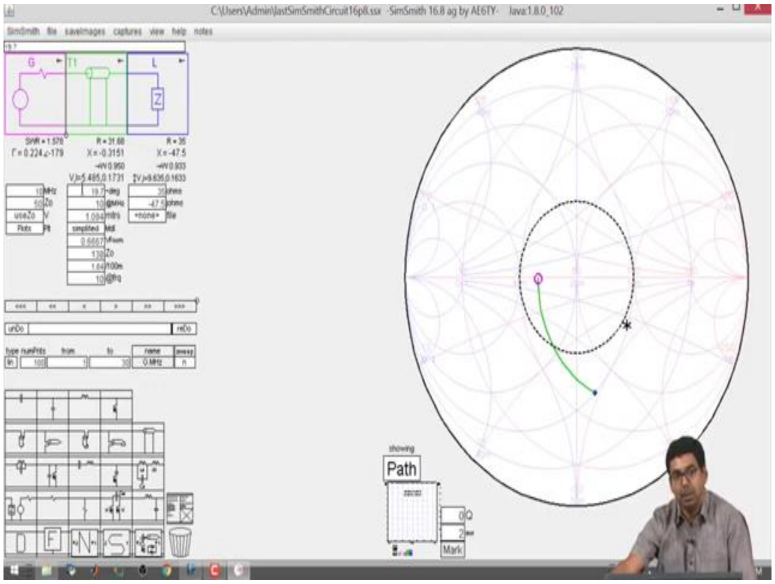

In some loads, it may be possible to do it, but it is not going to be easy to do this all right. Because there are two parameters; first, you have to figure out the length and then, you have to figure out the characteristic impedance and you are having a real characteristic impedance that is transform to some part and then it has to be matched with the load and then create a impedance of 50 ohms. So, this quarter wave length matching is good for resistive loads; it is not very good for complex loads. Then, what could be the approach? I mean I want to be able to match a complex load ah, but I want to use only transmission lines that is all I have to match. The approach is we can think about it in this way. Suppose I go back and I make the characteristic impedance to be 50 ohms, I try to understand first what the transmission line can do for me ok.

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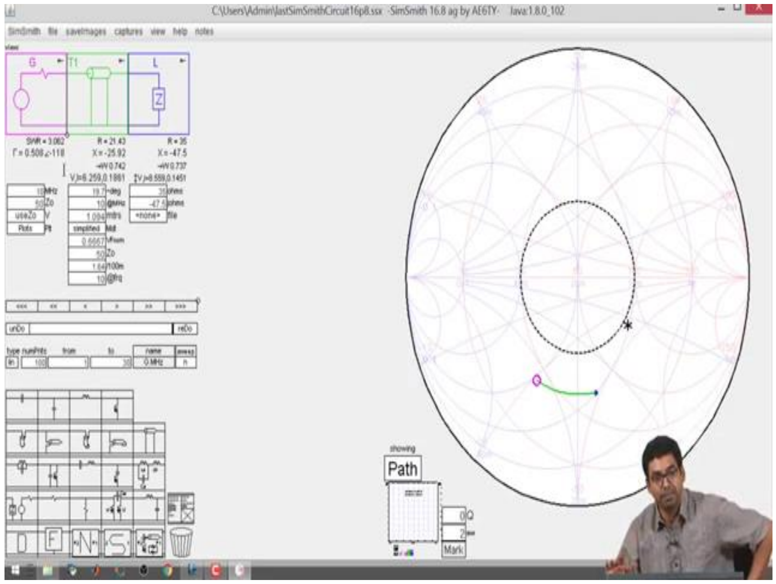

So, I keep increasing the length of the transmission line. So, I will be ok.

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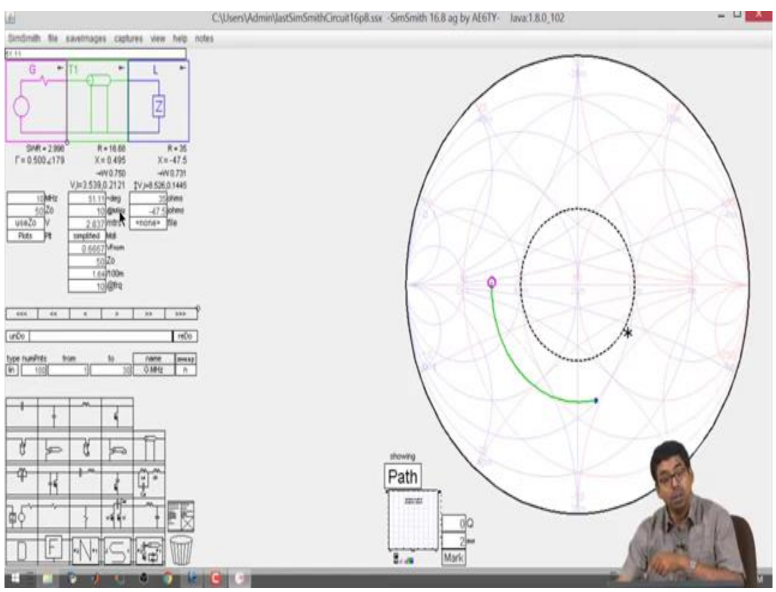

Yes, it goes to the horizontal axis, which means if I use a small portion of transmission line, I can make the complex load look like a resistive load at the generator because it cuts the axis over here. I will use a small section of the transmission line of 50 ohms, just matched over here to make it look like it's actually resistive with respect to the generator.

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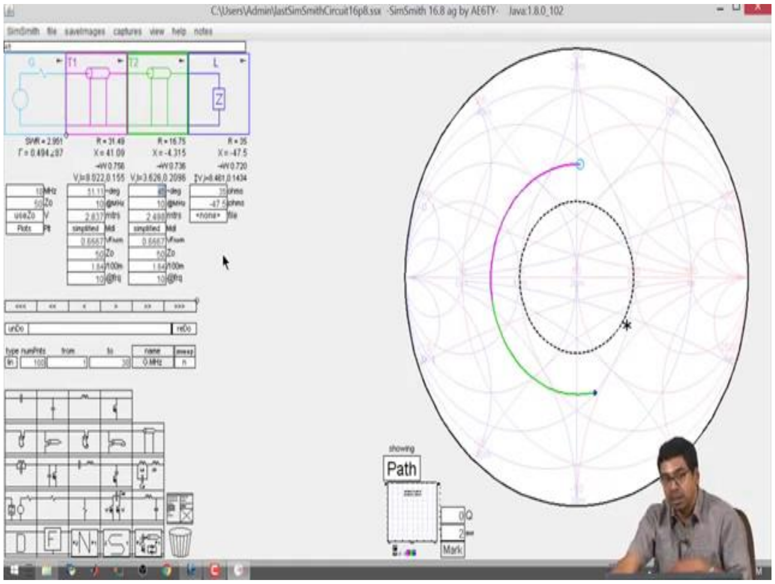

Then, I will add another transmission line section ok, I will add another transmission line section all right.

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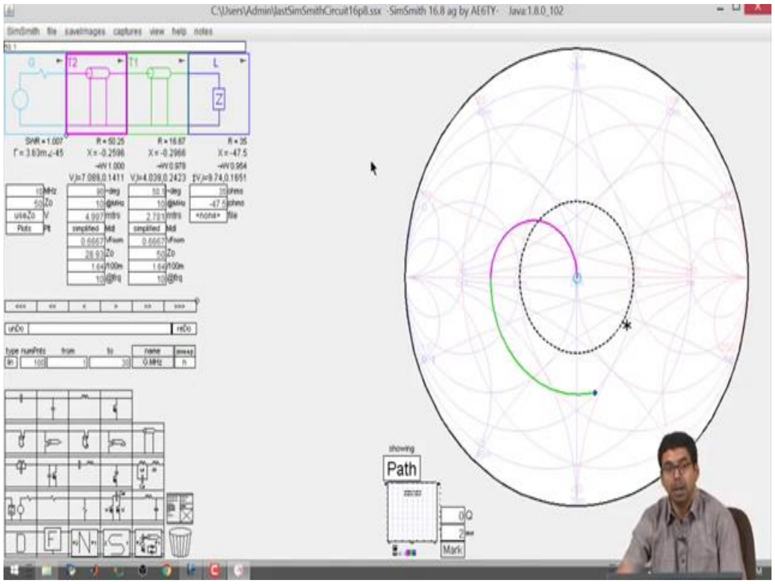

And I will make that 90 degrees and then, I will manipulate the characteristic impedance. Ops, I am in the wrong , a path that has to be in this way ok. I will make it 90 degrees and then, I will keep adjusting this. It is possible to map matches ok. Suppose, you want to use a quarter wavelength transformer like this, you will have to bring the complex impedance load impedance to the real axis first; you can use the transmission line to do that ok. A transmission line will take you around in circles of constant **VSWR** and the constant VSWR circles cuts the x axis two places all right. So, you can use either of them. And then, you can use a quarter wavelength transformer after that to match ok.

So, a complex load can also be matched with a quarter wavelength transformer provided you figure out that the quarter I mean the complex load can be made to look resistive first with respect to the generator. Then, you use a quarter wavelength transformer to match ok; it is a slightly tedious process. But again, the absurdity of doing this is granted that you will first bring the load to the a x axis that is done using a standard cable a say 50 ohms cable, only the length has to be adjusted which we are ok, it can be done. But then finally, to do the matching you still need something with the Z_0, which you know 28.93 in this case. So, you will have to manufacture a specific kind of a cable to do this again right.

So, the quarter wavelength transformer though can be used for bringing complex loads to the matching condition, you will still need to make custom cables and in many cases this is not going to be possible. So, the better approach is keep everything standard; only the load is going to be changing; however, we will match the load. There are two techniques. There are multiple techniques actually to do it all right, with the transmission lines itself people use what is known as a single stub technique and a double stub technique. Even within a single stub they have open stub or shorted stub all right; some people call it a series stub or shunt stub ok. So, you have then the double stub technique ok.

Now, what I will do is I will not go over the technique in great detail. But I am going to show you how it works all right and probably you can also start approaching impedance matching problems in this manner, if you are going to make hands on experiments. This is what a person would actually do right actually. So, I am going to first remove the abnormal portion and I am not going to remove both these transmission line sections ok, going to add a transmission line first ok.

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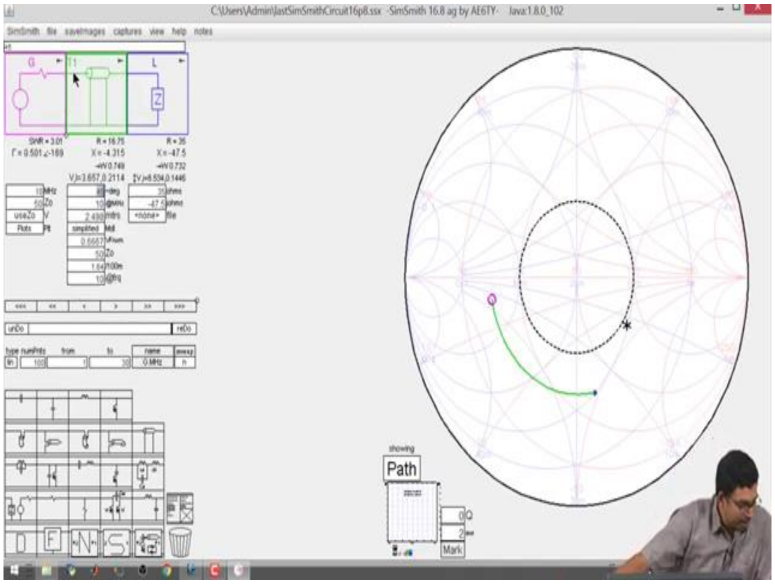

Now, this transmission line connected to the generator, I want to make it look like it is long, it is like a long transmission line. So, source is present somewhere, the load is present somewhere else, it is quite a long transmission line. 45 degrees seems really small. So, I want to show that it is a fair enough transmission line. So, it is 2.4 meters; let us say I want it to be 30 meters, which is realistic ok.

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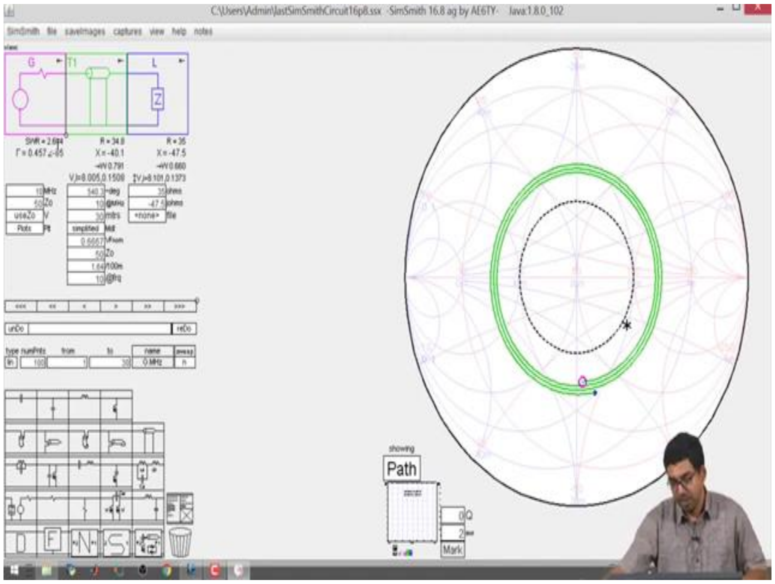

So, let us say that I want to make this 30 meters. Now, one of the things that I noticed when I did that is by default is instead of cutting the same circle again and again, it is spiraling inwards, in this case the spiraling inwards is happening because of the loss in the transmission line. The transmission line is lossy and if it is lossy ok, in the Smith chart with every 360 degrees going to keep spiraling inward, inward, inward extra all right and finally, you will reach the center the amazing thing is if I make this really long say 300 meters long, actually, I am getting closer to the impedance matching condition.

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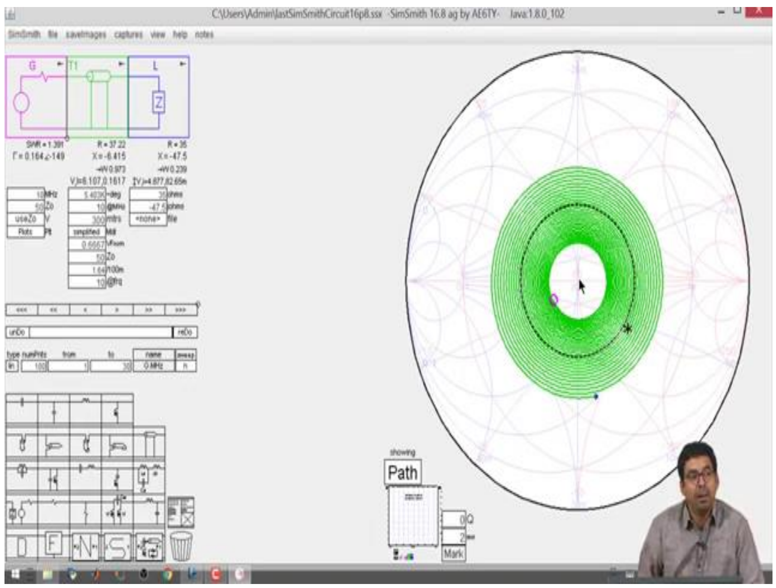

If I make it very long, say 3 kilometers or something, I am actually close to the center. The generator will not see any reflection, but the load also will not see any power ok. So, one has to be very careful about using lossless transmission lines ok, otherwise many things can happen. The center will believe that they are sending the signals since they are not getting any reflection going to the receiver, but the receiver will have the belief that there has been no signal sent, simply because the transmission line is eating all the power ok.

So, this is one way of impedance matching which should be totally avoided because you have matched the impedance in the worst possible manner, you have used more material to achieve the least amount of power delivered possible all right. So, what we start with is a lossless transmission line.

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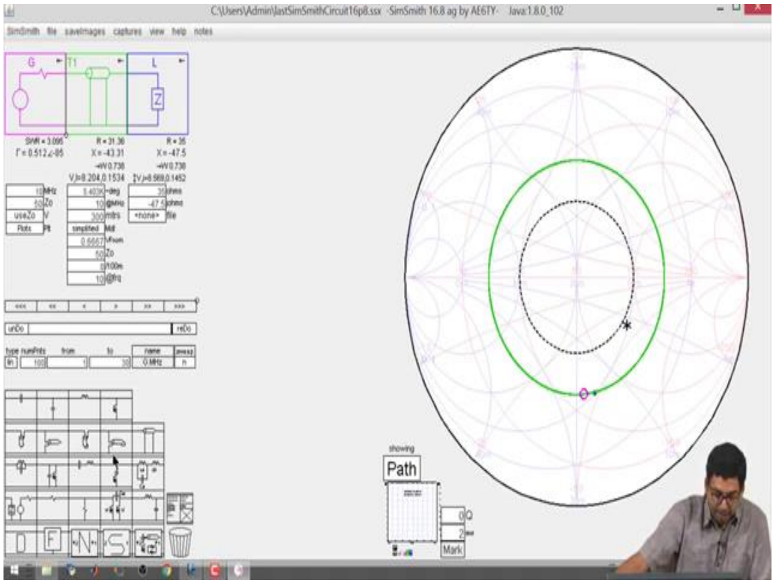

So, I will make this 0. Now, it looks like we can do something ok. So, a lossless transmission line is going over the same circle multiple times ok. Now, a short a I mean a I could connect a stub or a portion of a cable all right in parallel to it I am starting with shunt stub ok.

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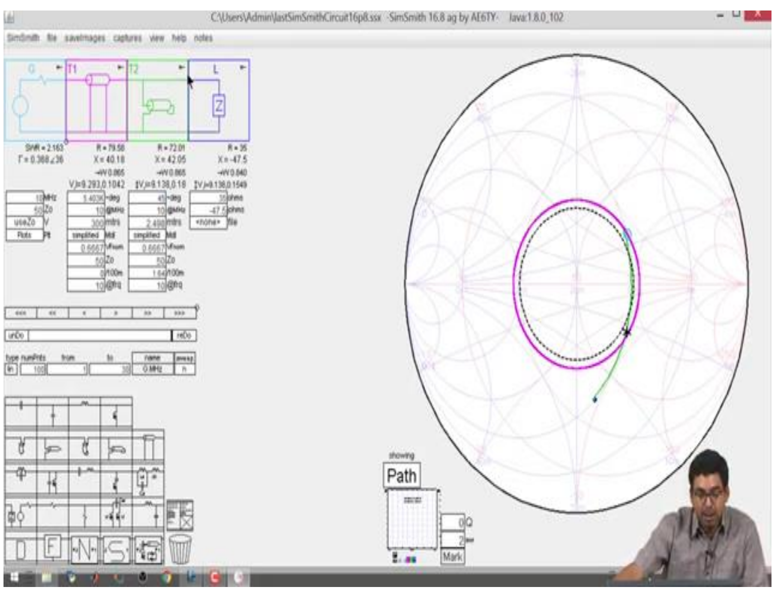

I want to attach this shunt stub here ok. The manner in which it is connected looks like it is directly in connection with the load. There are two parameters that we will have to work out in this shunt stub. The first parameter is how far away it should be from the load and the second is how long this cable, which is shorted itself, should be. These are the two parameters ok.

So, it is possible to match. I will show you in a minute how to match ok, but the two unknowns in this kind of single stub matching is the length of this stub itself and the distance from the load where this stub has to be inserted. But the good thing is we are using only standard components. So, 50 ohms is a characteristic impedance for all the components that is the advantage.

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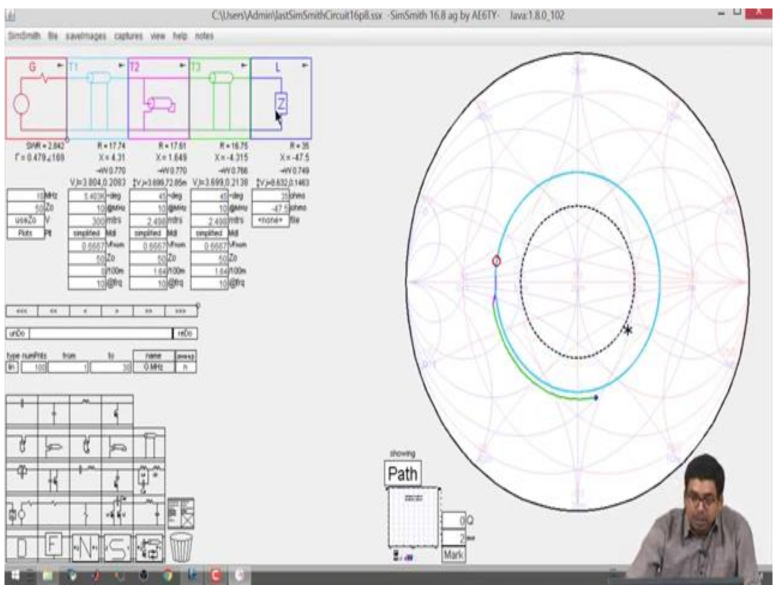

So, if I have to control the distance from this what I will do is I will put a another transmission line at the end like this to clearly signify that from the load, there is a distance of an ordinary transmission line and at that distance I have a shorted shunt stub after that there is a very long cable. So, towards the load and I am measuring from the load from some distance standard cable and then, I am having a parallel shunt stub ok and then I am having a very long cable to the left side. This is the set up.

Now, we have to just manipulate two things. We know that there are only two things present; one is the length at which you have to insert the stub length of the stub itself all right. So, you can start with this particular case all right.

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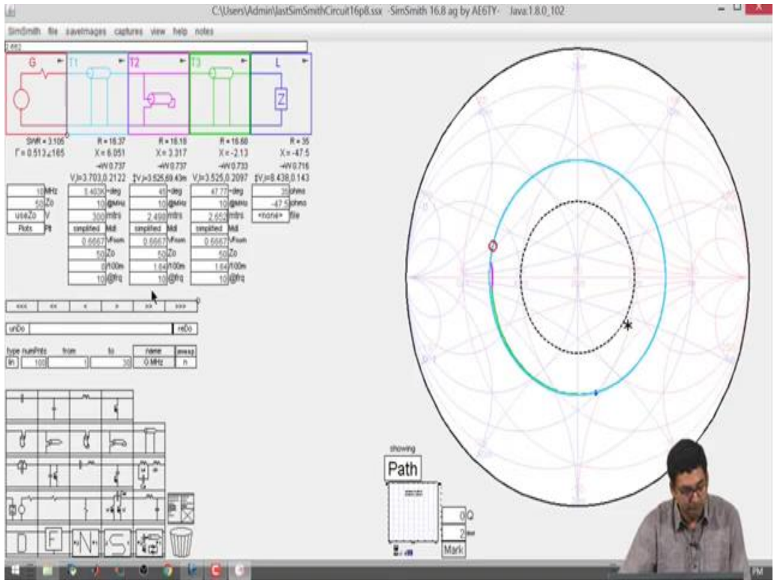

And then, you can start playing with length you can increase or you can decrease or just see you can do this.

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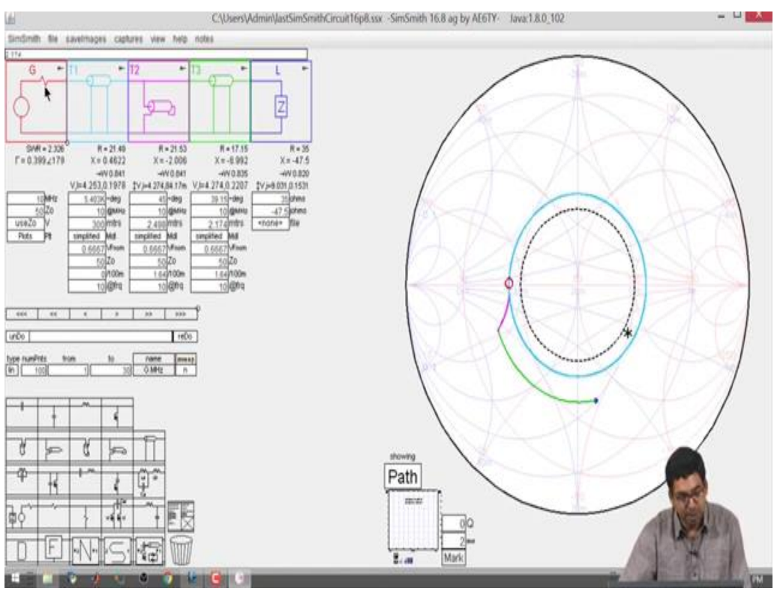

So, what we are aiming for is red color corresponding to generators now. Suppose we have added more components, red color corresponds to the generator. This red point has to come closer to the center of the Smith chart, whatever allows you to do that, you can do it. So, I am starting first with this part ok I am going to be changing the no length of it ok I get closer to the center, center and I am keep getting closer and closer and closer and closer and then, it starts going away.

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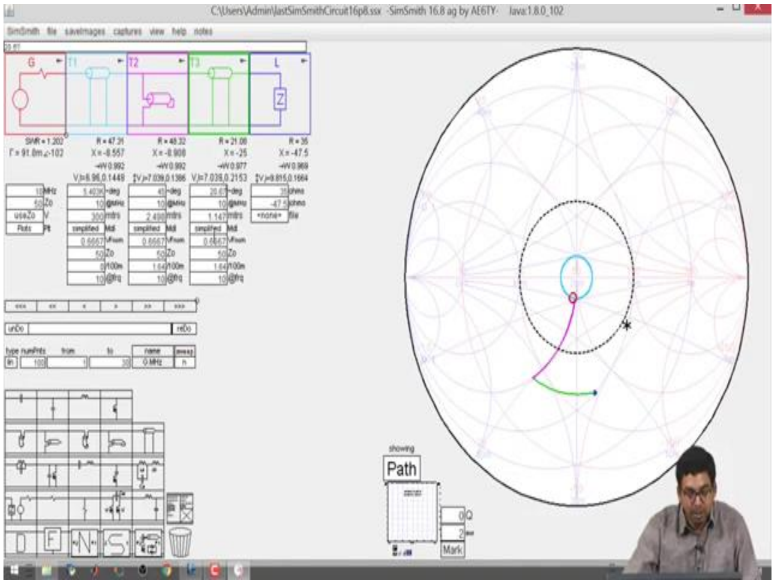

So, I will just know to get to the point where it is close to the G equal to 1 circle, I will stop there. Then, I will get to the short circuit stub and I can manipulate it to a length that is all right.

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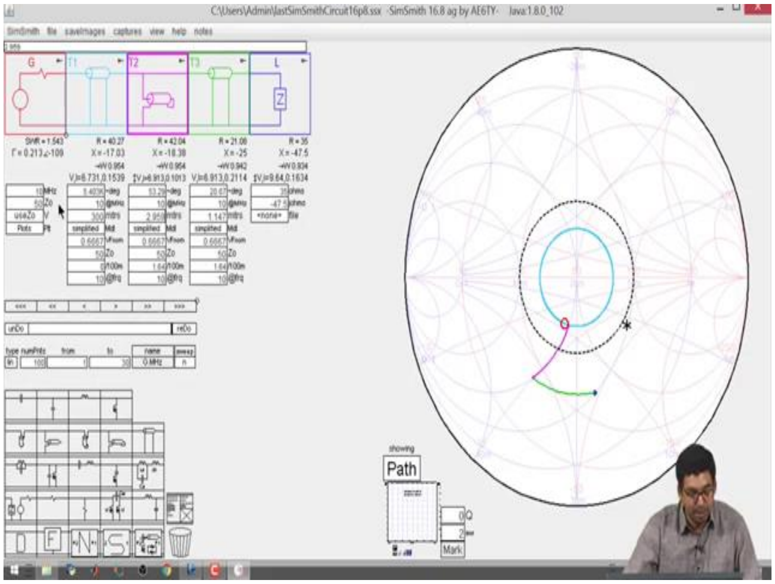

So, I will just see where I can increase or so, if I increase the length of this, it gets away; the red color point is getting away from the center. If I keep decreasing, almost there, almost there ok.

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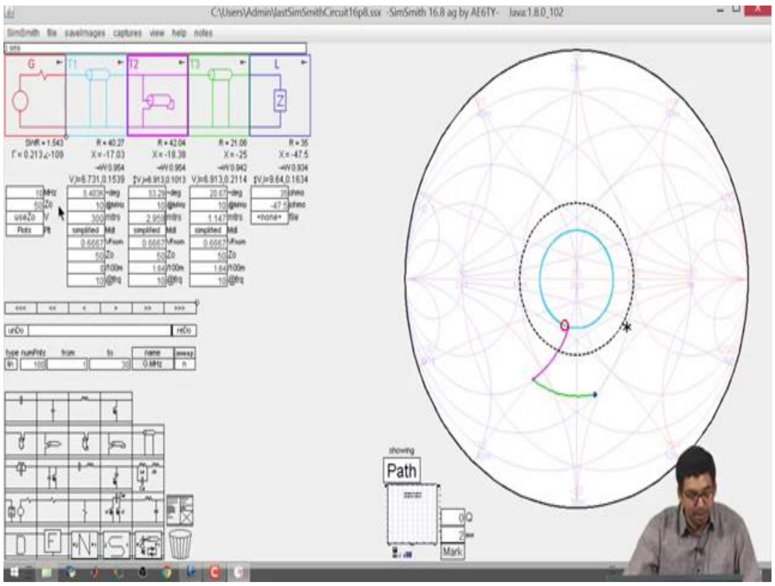

So, in this case the load was moved along a constant VSWR circle by a standard transmission line. A shorted parallel stub moved this to the center ok this process is known as single stub matching. You can also print the Smith chart and do it in very tedious ways, but I prefer to keep it in this way. When we are talking about single stub matching that is all, we just attach a section of the transmission at the end to figure out how long it should be. And then, figure out what is the length of the shorted stub that is supposed to be placed and then, manipulate till you are able to see the impedance go to the center. If you want to do it using a printed Smith chart, there are many tutorials available on the internet, you can go ahead, you can take a complex load.

In this particular case, I have verified I have taken the specific value from the problem in the book and I have seen that my solution is exactly matching ok. This is the simplest way and it will give you a feeling for what is happening. So, my suggestion is go back, install this program again, try to do all the gimmicks possible, vary everything till you understand what is going on. This particular tool provides you the ability to manipulate things and understand what is the effect of one thing on the Smith chart. This is single stub matching ok. So, I will stop here.