Indian Institute of Technology Kanpur
National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Applied Electromagnetics for Engineers

Module – 22
Fault detection using TDR

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Hello and welcome to the mook on applied electromagnetics for engineers in this module we will wrap up our discussion on transmission lines while discussing the importance instrument that is used in many places in order to understand the faults especially in the printed circuit boots, and in the older generation the problems in a transmission line cables okay, normal cable especially or the instrument which in the power transmission to locate an isolate faults these instrument is now works very much like fault.

By sending the no one pulse for a non step voltage and extracting the voltage that comes back because of the discontinuities, we know that whenever there is a discontinuity an incident voltage will be reflected from that point and then travels back towards the source or the generator by monitoring this voltage which is coming back we can then kind of lock it where the load voltage is and in fine to also determine what kind of a discontinuity whether it was an open circuit or short circuit induct term or capacity when the reflected voltage comes back and the instrument.

Which does all this for you is called as a timed domain reflective meter and we will give you the basic principles of time domain reflected meter of course the complete study of TDR is something that is beyond the scope of this subject, now as worm of exercise to TDR let us look at a few cases.

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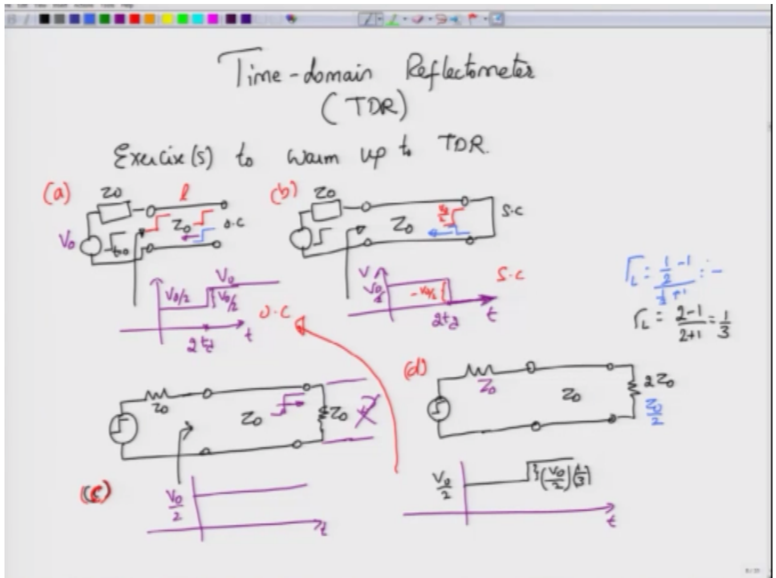

Which I have drawn already here so I have a case A here, here I consider a stepped voltage which is launched at T = 0 to the transmission line circuit okay of some length we do not need to worry about what is the length of the transmission lines here but to know that the characteristic impedance of the transmission line is given by Z_0 which is real we will assume that, and the source is called so having the impedance of Z_0 so inside we have to design an instrument such that the source impedance.

Must be equal to the characteristic impedance in fact it can you can do that one and then we do it we have pulse generated with an impedance of Z_0 connecting to a transmission line of Z0 let say you know largest as the step begins to propagate you know it begins to propagated arrives at the open circuit, what will happen to the open because of the open circuit there will be a reflected wave what would be the shape of the reflected wave the reflected wave will also have the same shape.

Because $\gamma l = +1$ here so the reflected wave will travel back, so if you monitor the voltage at this point which is at the input terminals of the transmission line okay, and sketch what kind of a voltage you are going to observe we will see that the voltage that we receive will be initially a launched voltage of sum V_0 / 2 assuming the step has an amplitude of V_0 so we see that the launch voltage step i8s V_0 / 2 because it propagates there and the time TD this voltage V_0 / 2 will be further added because of the reflected voltage.

Travelling back so you will see added time T = TD the voltage will be as jump of V_0 / 2 therefore the total voltage here is V_0, and of course this remains as it is because there are no further reflections okay, now let us look at the case where we have a short circuit, in the short circuit case the initial voltage that would be reaching the step will be of V_0 / 2 but because a short circuit has reflection co efficient of – 1 will invert the voltage symbol and then send it back towards the source.

So if we now sketch what happens to the voltage at the generator or input terminals of the transmission line you see that, initially you launch a voltage of V_0 / 2 at time T = TD or rather through TD this may correction in the earlier figure also at time2TD the voltage will actually jump down and becomes 0 thereafter, there if some want to give you these two wave forms that we have sketched you will be immediately knowing what kind of a discontinuity that existent because here is a jump upwards of magnitude V_0 / 2 before the total voltage that the generator sees will be equal to v_0 = after time 2TD.

Here the total voltage that the generators c is will be = 0 write after time 2TD therefore there is a voltage jump of V_0 / 2 or other – V_0 / 2 so because in one case the voltage is jumping up and in other case the voltage is jumping down completely you know you can know very well that this here open circuit case this is a short circuit case okay let us consider couple of other circuits here we have a transmission line to be terminated with a load whose impedance happens to be equal to the characteristic impedance.

And we know very well that if I start monitoring voltage at the lowered side I see there are no reflections why would I see more reflection because when the voltage here approaches you know the step voltage of amplitude V_0/2 approached the load here it would be completely absorbed the reflection coefficient here is 0 therefore it would be completely absorbed.

In other words this is almost I mean this is although the case of a infinity long transmission line so that the large voltage would never come back so this is the condition that you will have finally if we go to the situation that is shown at this point okay so I have the characteristics impedance at not of the line but I first terminated with to Z^0 okay.

If I terminated with to Z^0 I know that the reflection coefficient corresponding to that will be 2-1/2+1 which is equal 1/3 but the reflection coefficients sign is positive okay so if you monitor the voltage up to 2Td you will have $V_0/2$ at then you see a jump and the magnitude of the jump will be $V_0/2$ incident voltage amplitude times 1/3 okay.

So this is the jump that you are going to see again by noting the difference between the case say C here this is the case B that we have to consider finally the case D that we have this point so this is the case C that we have so you can clearly see that although there is jump in case D the jump is not of the magnitude $V_0/2$ so therefore this case D will be different from case A.

In case A the jump is actually completely $V_0/2$ where as in case D the jump is there but the amount is not $V_0/2$ it is just slightly above but if I know how much is the voltage jump I can easily find out what is the value of the load that is connected because I know what is the characteristic impedance I know what is the amplitude of the voltage that we have sending so from this two values knowing what is the jump in the voltage I can find out what is the value of γL.

Now if I consider the last case where we terminate the transmission line with$Z^0/2$ what kind of voltage do I get I can find out what is γL corresponding to $Z^0/2$ so that would be 1/2 -1/1/2+1 I am not really looking at the answer here but to just understand that the reflection coefficient will be negative here right.

So the reflection coefficient will be negative here and therefore instead of jumping up you will actually see that there is a jump in the opposite direction that is well actually see the voltage reducing at time 2Td okay so you see that if the voltage is jumping you can immediately claim which would be correct that the lowered resistance that we have kept will be greater than Z^0.

If you say that voltage to be jumping down or going negative compare to $V_0/2$ it is going in the other direction then you will say that RL is less than Z^0 so you can distinguish between two cases RL is greater than Z^0 RL less than Z^0 you can of course distinguish between the case of RL is equal to Z^0 for RL equal to Z^0 there will not be any voltage change.

If you monitor the voltage at the input terminals okay and by knowing the magnitude f the jump even in the positive direction or it is above $V_0/2$ or below $V_0/2$ you can then estimate what would be the resistance of the load okay so if I worked to builds an instrument that perhaps looks something like this.

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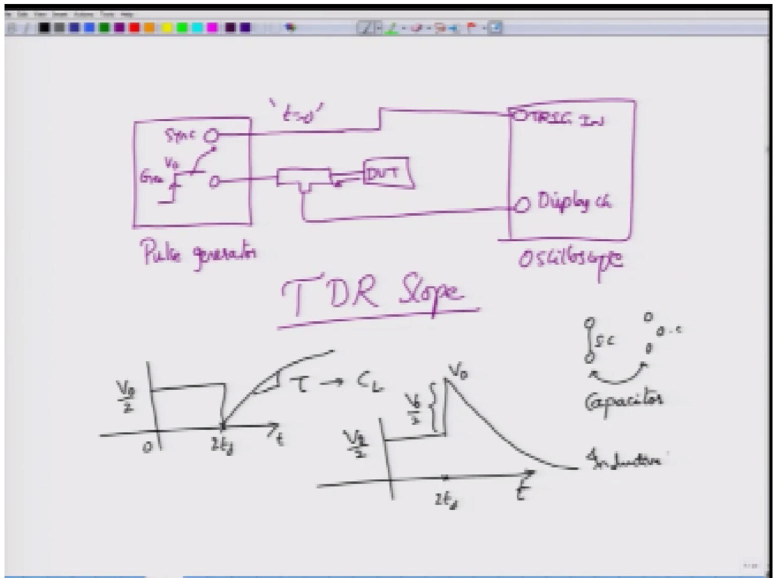

So I have a pulse generator so this is the pulse generator that I have and let us say there is a sink but and for this which will along the pulse generator to synchronize with the oscilloscope so please note that this oscilloscope must be a real time oscilloscope in commercial Td the oscilloscope and pulse generator are build into the same kind of the system okay.

From the sink you send out at trigger pulse okay so this reaches trigger input of the oscilloscope so that will allow you to synchronize the two pulses so when you actually sending the pulse so you need a T=0 for your pulse generator right so that T=0 condition is given by the sinking condition or the sink to the trigger in then you actually have a pulse or step generator okay, so you have a step or a pulse generator here it could be both so pulse TDR also exist step TDR is also existing. What we do here is, we divide this particular pulse which is having an amplitude let us say v_0 here okay, so I consider an amplitude of the pulse to be v_0 I consider or rather I divide the power into 2.

So one I connect this one to the device under test and the other input I considered it to be the channel input of the oscilloscope, so this is the channel input for the display okay, so this is the display to the channel that I have connected on the oscilloscope. So whatever device that I connect will be the device that I am testing, so when this step goes the step will trigger the generator by the sink function so whenever the step is generated at this point the trigger pulse will send an input so when the oscilloscope is now trigger and it will display the triggered step as such.

And then when the step goes to the device under test so there will be part of the step that would be already visible on the display so it kind of just gives you a nice visual outlook okay. However, any reflected voltage that comes back from the device under test that you have kept it could be a transmission line, it could be a intend circuit board, it could be anything that you have connected would falls your train to determine that reflections because of the discontinuities would come back and would be further displayed, okay.

So this is an example, of what is called as a TDR scope okay, so a TDR scope by monitoring the voltage at the input terminals of the transmission line allows us to say or find out the nature of the discontinuity and also the point at which you obtain discontinuity. Let us look at a few more examples, let us say this time this we start with a certain voltage that we measured on the TDR scope, so the output voltage of $v_0/2$ is propagating at some time 2td as measured from the time access that is present with that oscilloscope.

We see that the voltage is of this nature, what can you conclude from this, you can see that initially the voltage must drop down so initially there must be a element which acts like a short circuit and eventually the element must act like an open circuit so that the compute voltage is reflected back, and an element which does so initially acting as a short circuit and eventually acting an open circuit is a capacitor, right. A capacitor acts as a short circuit initially and then open circuits, because of the short circuit the voltage will completely go to 0 and then it will rise up to infinity.

Assuming that this is the only discontinuity that I have, I can actually measure the charging time okay, from there I can find out what is from the value of τ I can find what is the load capacitor that I have used, okay, suppose instead of receiving this type of a voltage what I receive is a voltage that would look like this so I have $v_0/2$ and at sum 2td so I receive at sum 2td, I receive a voltage that would go like this, so there is a jump of $v_0/2$ and therefore the total voltage at 2td will be equal to v0. What kind of a load is this, this is a inductive node okay.

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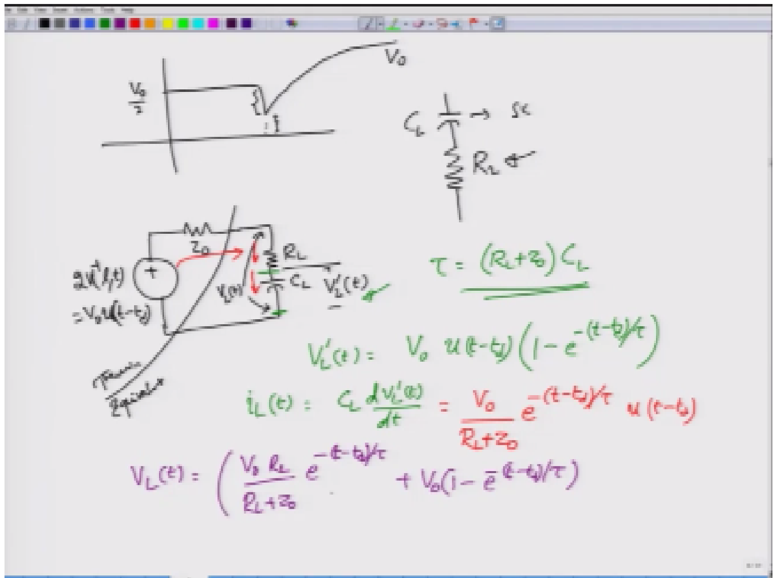

Now consider this case, suppose I receive some voltage of this nature instead of going completely to 0 just goes barely to 0 and then eventually starts to go and reaches v_0, so initially you have $v_0/2$ the jump here that you would see is not $-v_0/2$ it is only just a bit of a jump so this voltage is not reaching, see do so all these voltage is remaining with us, so what kind of a discontinuity could this be we know very well that the capacitor must act like a short circuit and hence we will pulling the voltage down correct.

But since the capacitor is not pulling the voltage completely down there must be some resistive element okay, which will be less than z_0 otherwise this voltage would not have been less than like that, so there will be some resistance less than z_0 which is pulling the voltage down and then it is increasing to v_0, okay.

What I wanted to say is that, initially you have a capacitance okay, but the capacitance is not the alone discontinuity that you have in series with the capacitance there must be an inductor so that a fraction of the voltage is you know actually developed reflected back and then get you know gets added t it. Eventually the capacitor will start to you know charge up to the full voltage and becoming a open circuit.

So what you should have is not just a capacitor but also a load resistance R_L and the amount of jump that you would see would clearly be the voltage that the load R_L will carry so let us actually solve an equation for this, I will set up the equation and then I will give you the solution, you can verify this, so assume that we $2v^{+}\gamma^{t} = v_0\, u\,(t-t_d)$ as the pulse that would be appearing through the load or the characteristics in the place of the transmission lines z_0 to this series combination of resistor R_L and the capacitor C_L.

So if I a call this voltage across this load, as V_L of t and the voltage across the capacitor itself has some V_L prime of t, so I will call this as V_L prime of t, please remember this par is the equivalent in a circuit right, this was the thavenine equivalent circuit that we had and then you have V_L prime of t, it is just the voltage across C_L, where as the complete voltage across the discontinuity which is R_L in series with C_L is given by V_L t.

What will be the nature V_L`t? we can see that if I kind of find out what is the characteristics what is the charging time, I can see that the time constant T must become $R_L + z_0$. How do I find the time constant? I will make the source and short it to 0, to disconnect theses thermal see in green and then find out the total resistor in the circuit. That would be $R_L + z_0$, so that is the equivalent R and there will be a C_L which corresponds to the time constant of RL + $z_{0\ x}$ C_L.

Therefore the voltage across this load or across these capacitor V_L prime of t initially will start at 0 because we have consider this as to = 0 and from there it will grow in the extensional manner to $R_L + z_{0\ x}$ C_L, so I can write down V_L`t as sum $V_0$ okay u (t-$t_d$) x 1- $e^{-t-dt/T}$ where T is $R_L + z_{0\ x}$ $C_L$ okay. What would be the current $i_L$ of t here? The current $i_L$ is given by $C_L$ $dv_L$`t/ dt please note that I have actually consider the voltage just across the capacitor but if I calculate what is the current through this one?

The same current will be in the entire loop here, so I can find the current through the capacitor from that one that would be the same current everywhere and this is given by if you evaluate and simplify the equation you will that it is given by v_0 $R_L + z_0$ $e^{-t-dt/T}$ is the usual thing and the voltages are starting after a time t= td. You can now go back and calculate what is the full voltage vL of t, that is across R_L C_L and you will see that you will have 2 parts to this v_0 R_L $R_L + z_0$ okay which would be changing by T + v_0 1- $e^{-t-dt/T}$ .So this would be the total load voltage, of course this entire thing multiplied by t-td.

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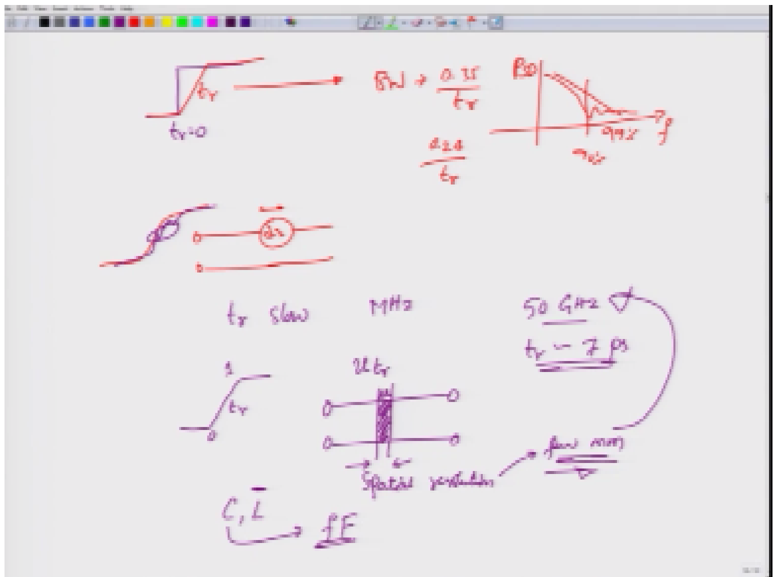

What is interesting is the reflected voltage, you can go back and subtract the insidiously voltage from the previously calculated v_L of t and what would you get from the reflected voltage is again 2 components, one components v_0 R_L R_L + z_0 okay which would be decaying right with the time constant of the same value that we have considered + v_0 ½ - $e^{-t-dt/}$ okay. This entire thing multiplied by u (t-td).

So look at the nature of this reflected voltage, the nature of this reflected voltage is that at t = td the term will be = 1 here, the term here = 1, so ½ - 1 will be -1/2 of v_0 right. so it would be-1/2 of v_0 which is the term which you actually expect, at time td you know for the reflected voltage because there is the capacitors out there, but then this voltage will not be completely -v_0/2 but it will be added to this v_0 R_L R_L + z_0, so the complete step of -v_0/2 would have been here than the actual voltage that you see is given by -v_0/2 + v_0 R_L R_L + z_0, so v_0 R_L R_L + z_0 are again very obvious.

We started off with some v_0 step voltage okay again you had then you had z0 you had Rl the capacitor momentarily had become short circle rate eh so the voltage across this +0 the entire voltage vl (t) was this fellow which is simply from the voltage divider giving you v0 Rl / Rl+ z0 okay. Once you see a jump here eventually the voltage start to build up.

So T – td going of the infinity this first term will go to 0 and in the second term here the exponential terms will go to 0 and you reach some v0/2 you know assume to erratically with the time constant of Rl + z0 x C. And if you look at the source voltage now so initially you are putting out a voltage of v0 /2 and then there will be a jump here the amount of jump that you are going see down which is not completely gone to 0 is clearly this one that is marked in the red circle okay from here it will go on eventually assume to erratically reaching v0okay.

So by looking that the magnitude of the jump we will be able to find out what is value of Rl on the other hand if you obtained a voltage expression that coming voltage way form it look like this and the PDR which would not completely jump up but only jumps slightly up okay and it eventually go to 0 you known that this should have been complete jump had only an inductor been present.

However because there is a gap now right this would more likely be inductor in series with the resistor okay so there will be Rl and some ll indicating load that is series combination of r and l okay. So this is how a tdr by looking at the tracers will be able to identify what was the actual nature of discontinuity. Couple of points about tdr is that if you back to the pulse generator the tdr.

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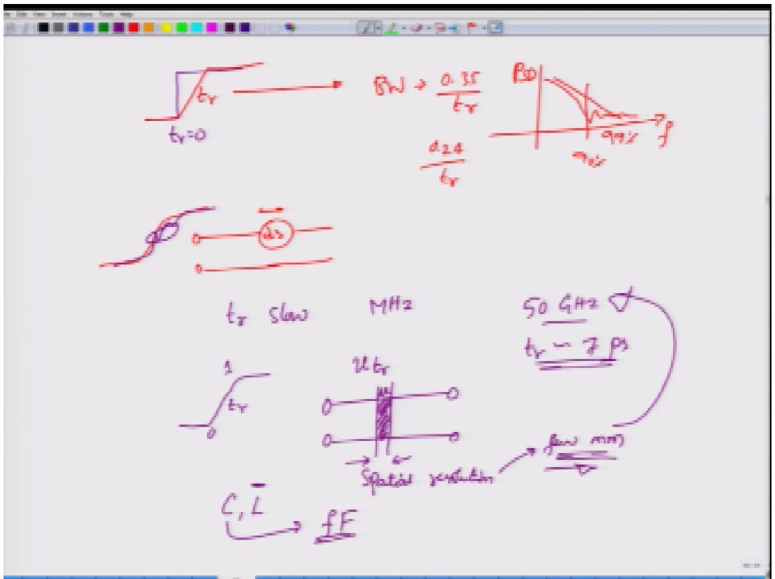

This is the idea pulse that one would like so tr = 0 okay. However in practice the pulse that would be generated would more likely have a certain tr, corresponding to this tr there will be a certain band width which is about 0.35/tr where about 99% of the power spectral density would have gone out okay so this is about 99% in terms of the frequency this is power spectral density, so that band width is about 0.35 / tr if you are happy with 90% value then you can even use a slightly non conservative estimate of 0.24/ tr.

Most importantly if there is a salt okay so there is some discontinuity here on the transmission line okay and the discontinuity happens to be such that whose you know the location happens to be such that the time delay to reach the pulse to reach here and then come back would be less than this tr then even has the pulse is changing slowly right, this happens with the slow tr the reflection would have come and then it would you know cause the total to go something like this I have not derived all this but you can actually do that one by looking at the references which I would suggest during the course.

So you would see that this amount of small distortion would not be visible properly and it can we completely masked okay. So if the raise time is slow so a slow value of tr corresponds to a band width in the range of say mega hertz region will not be able pick up faults or resolve faults why because when the voltage is changing from 0 to some value one let us see over a time tr each point is no traveling on the transmission line.

So corresponding to a time change of tr the corresponding length change on the transmission line here will be tr times u where u is the velocity of the voltage wave here. So when the raise time tr is such that or whatever the raise time that you have any fault that would occur here two fault let us say will not be able to distinguish. So this is in fact the special resolution of a you know at tdr type of a instruments and it is same as an optical tdr or as a simple red r.

So whenever the raise time is slow the corresponding length on the transmission line within which discontinuities can be resolve the special resolution will also be low. Modern trd can resolve or have band width of about 50GHz or slightly greater than that indicating tr of about 7 ps okay. So very short raise time which means resolution the special resolution is a few mm this is impressive because any tdr that can resolve in a few mm where the faults are located is actually quite impressive, the reason being you need to support a very high band width.

So the electron x that need to support the very high band width required by tdr scope will also grow that much more expansive okay so modern TDR’s have TR less than 10 peco second and corresponding large bandwidth and excellent spatial resolution so which means any discontinuity which is just about a few millimeters will be able to be resolved, okay.

The corresponding capacitances and inductances that you can measure are very small, in fact if you can measure capacitances of a few femto faran which is certainly not possible with a traditional LCR meters okay, traditional LCR meters cannot measure in such very low capacitors whereas a TDR can easily do that.

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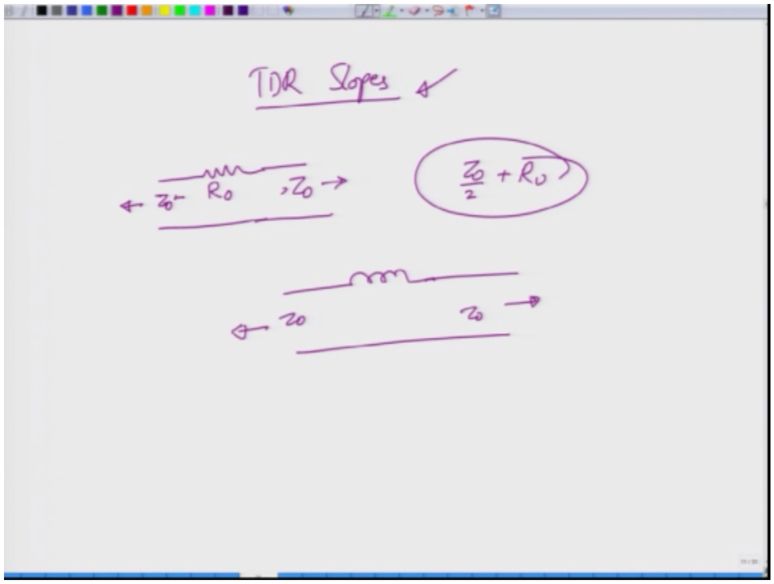

And inside display nicely the corresponding graphs to you, okay so a catalogue of TDR scopes are available in the internet my suggestion is that look at the TDR scopes okay, and then try to estimate from you know whatever the equations or from your knowledge of LC and R what should be the discontinuity so as to produce this type of a voltage. As an example, consider what happens if I have a series discontinuity of say R0 okay, on a transmission line so this is all the transmission line having z0 impedance, z0 impedance okay.

So if you are able to pin down what would be the TDR scope for this then you would have understood not only how a TDR works, but also understood how to calculate reflection for your hint you see that the impedance in here is z0 the impedance in here is z0 therefore the total impedance seen will be z0/2 and that would appear along with R0, okay.

So you can see what would happen to the scope if you actually work out the equation or you can see what happens to a series inductor with transmission line having z0 here and having a z0 over this side, so you can find out what would be the corresponding TDR scopes so this brings us to the end of the first major sub topic we have considered in the course that major sub topic was transmission life we are understood transmission lines both from the steady state point of view as well as the transient point of view.

We will now begin to actually go to the second major topic which is electromagnetic oaky so far we have avoided even bringing maximum into the picture but that was because you are able to get away with this analysis without using maximum equations all that was required was extend the notation of voltages in the currents and this extension is not trigger it Is not just simple that we have extended voltage in the current.

We have seen that or any piece of wire which will act like a transmission line this voltage or the current will be in the form of a way okay so in the next modules we will actually begin by starting with of few mathematical preliminaries then we will jump right into Maxwell's equations and then study the consequences of this Maxwell statement measures thank you very much.

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