Course name: EMI /EMC and Signal Integrity: Principles, Techniques and Applications.
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Lecture 45: Time Domain Crosstalk

Welcome to the lecture of the course on EMIMC and Signal Integrity Principles, Techniques and Applications. In the last class we were discussing the frequency domain crosstalk with common impedance coupling included. So, just I will have a problem on this and then we will move to the time domain crosstalk analysis. So, I think in the last class we have seen that ah how to find the find out the crosstalk coefficients for common impedance coupling. So, total coupling is the sum of inductive capacity and common impedance coupling. So, we can write that this is this two are frequency dependent terms and the common impedance coupling is not dependent on frequency. Similarly, the far end crosstalk transfer function can be written as. So, common impedance ok. So, with the help of this we can start solving a problem.
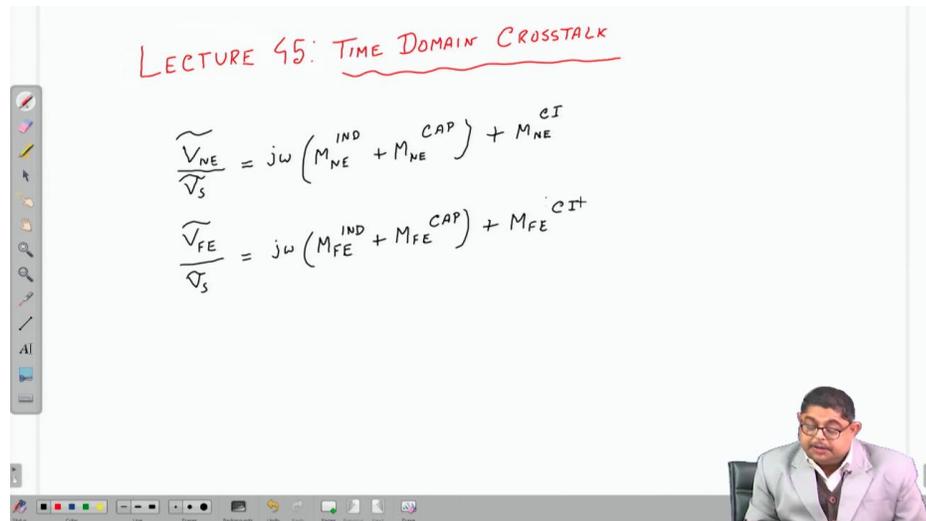
So, consider a 3 wire ribbon cable whose the cables radius is 7.5 mils separations that is there the separation D that is 50 millimeters. So, let these be the reference this is the generator this is the receptor. So, and line length L is given as 4.737 meter the terminating resistances are R s is equal to 0 R L is equal to R n e is equal to R f e is let us call them R the per unit length resistance of the lines is given as 0.194 ohms per meter

and the operating frequency is 6 megahertz. Now, the job is what is the crosstalk for R is equal to 50 ohm this is to be find out.

Now, first we will have to check whether the line is electrically short because our model is that. So, what is the lambda at 6 megahertz we can calculate it the 3 into 10 to the power 6 10 10 to the power 8 into 6 into 10 to the power 6 meter. So, that is 50 meter. So, L by lambda is 0.09. So, generally 0.1 if this ratio is we can consider is electrically short. So, we can say that so, line is electrically short. So, our model is valid now also this is the first time we are seeing the common impedance coupling. So, what is lumped resistance lumped R 0 that will be R 0 into L. So, that is 0.194 into 4.737 and that comes to be 0.92 ohm. Now, if you look carefully that already ah this same where we have this type of system we have analyzed before for their characteristic impedances exactly the same value only the loss is included now. So, the same length etcetera. So, for this case we have already calculated L and C matrix otherwise you can calculate, but I will take those in a previous example we have done this line. So, L matrix ah we know. So, from L matrix we know L g is equal to L r is equal to 0.76 microhenry per meter L m is 0.24 microhenry per meter then C g is equal to C r is 11.1 pico farad per meter and C m was 5.17 pico farad per meter and we have seen that Z c in presence of others that means, Z c r or Z c g both are Z c r is equal to Z c g that time we calculated these. So, that was 261.5 ohm ok. So, now, it is given that the all the terminal impedances are 50 ohm except R s source impedance that is 0.

$$\lambda = \frac{3 \times 10^8}{6 \times 10^6} \, m = 50 \, m$$

$$\frac{x}{\lambda} = 0.09$$

So, line is electrically short

Lumped $R_0 = r_0 x = 0.194 \times 4.737 = 0.92 \, \Omega$

$$[L] \rightarrow l_G = l_R = 0.76 \, \mu H/m$$
$$l_m = 0.24 \, \mu H/m$$

$$C_G = C_R = 11.1 \, pF/m$$
$$C_m = 5.17 \, pF/m$$

$$Z_{cR} = Z_{cG} = 261.5 \, \Omega$$

So, we find the ratio R L by Z c g into R n e or R f e because both are same and both are required in two different cases R n e by Z c r what is this value 50 by 261.5 into 50 by 261.5. So, this ratio is much less than 1. So, we can say from the start that inductive coupling will dominate that is the condition for dominance of industrial coupling. Now, we can find the near end cross talk transfer function for different types of coupling. So, this M n e inductive that the formula we have derived in the last class R n e by R n e plus R a p L m by R s plus R L. So, R n e R n e R a p all are same value. So, this ratio will give a half then L m L m was 0.24 microhenry per meter. So, 0.24 into 4.737 microhenry we are getting 10 to the power minus 2 by R s is 0 R L is 50. So, this if you calculate you will get 1.1369 into 10 to the power minus 8. Similarly, we can find the M n e cap that will be R n e R a p by R n e R L. So, this will be again this will be 50 into 50 by 100. So, this will be half into 50 that is equal to R L R L is again 50 and C m is what is the value of C m C m is 5.17 picofarad per meter 5.17 into 10 to the power minus 12 into 4.737 meter. So, 50 into 50 by 100 ah. So, this will give rise to 6.12 into 10 to the power minus 10.

$$\frac{R_L}{Z_{cG}} \quad \frac{R_{NE} \, (\text{or } R_{FE})}{Z_{cR}} = \frac{50}{261.5} \times \frac{50}{261.5} < 1$$

$$M_{NE}^{IND} = \frac{R_{NE}}{R_{NE} + R_{FE}} \frac{L_m}{R_S + R_L}$$
$$= \frac{1}{2} \times \frac{0.24 \times 4.737 \times 10^{-6}}{50} = 1.1369 \times 10^{-8}$$

$$M_{NE}^{CAP} = \frac{R_{NE} \, R_{FE}}{R_{NE} + R_{FE}} \frac{R_L \, C_m}{R_S + R_L}$$
$$= \frac{1}{2} \times 50 \times 50 \times 5.17 \times 10^{-12} \times 4.737$$
$$= 6.12 \times 10^{-10} \quad +$$

So, clearly the inductive coupling is dominated then M n e ah this is C i it is R n e by R n e by R n e by R L plus R a p R 0 by R s plus R L. So, this ratio is half and this ratio is 0.92 by 50. So, that gives is 9.2 into 10 to the power minus 3. So, it is now you see that the common impedance coupling is quite significant it is much greater than inductive coupling even though the resistance are very small compared to R n e R a p etcetera. The per unit resistance of the lines that was only 0.194 ohms per meter, but for coupling it has contributed significantly, but one good thing is it is not frequency dependent. So, now, we can write the transfer function V n e by V s is equal to j omega M n e I n e plus M n e C a p plus M n e C i. So, it is j 2 pi f into 1.14 into 10 to the power minus 8 plus 6.12 into 10 to the power minus 10 plus 9.2 into 10 to the power minus 3. So, this ah the inductive and capacitive coupling their total is getting multiplied by f by that it is overtaking the common impedance coupling, but still common impedance coupling is not very small because at 6 megahertz if you do. So, f is 6 megahertz means it will be 10 to the power minus 2 into 7.55 let us take it 8. So, 8 into 6 is 48. So, that will be 0.48 this will be 0.09. So, 0.48 and 0.09. So, common impedance coupling should not   be neglected if you want to perfect your model similarly you can also find V f e by V s s.

$$M_{NE}{}^{CI} = \frac{R_{NE}}{R_{NE} + R_{FE}} \frac{R_o}{R_s + R_L}$$

$$= \frac{1}{2} \times \frac{0.92}{50}$$

$$= 9.2 \times 10^{-3}$$

$$\frac{\widetilde{V}_{NE}}{\widetilde{V}_s} = j\omega \left(M_{NE}{}^{IND} + M_{NE}{}^{CAP} \right) + M_{NE}{}^{CI}$$

$$= j\, 2\pi f \left(1.14 \times 10^{-8} + 6.12 \times 10^{-10} \right) + 9.2 \times 10^{-3}$$

$$= j\, 7.55 \times 10^{-8} f + 9.2 \times 10^{-3}$$

Now let us see what happens if that R value that means, all terminal impedances are made. So, this is a low impedance case that ah R L was 50 ohm now let us see high impedance case. So, let me take R is equal to 1 kilo ohm ah 1 kilo ohm. So, let me quickly calculate this that M n e i n d will be half into 0.24 into 4.737 into 10 to the

power minus 6 by 10 to the power 3. So, this will be 5.7 into 10 to the power minus 10 M n e cap will be 10 to the power 3 by 2 into 5.17 into 10 to the power minus 12 into 4.737. So, that will be 1.22 into 10 to the power minus 8 M n e common impedance coupling is half into 0.92 divided by 10 to the power 3. So, that will be 4.6 into 10 to the power minus 4 clearly here you see that capacitive coupling is dominating that was the case because when we started we said that the for low impedance load inductive coupling dominates for high impedance loads capacitive coupling dominates. So, that is evident here. So, the total coupling in this case will be V n e by V s is J 2 pi f 5.7 into 10 to the power minus 10 plus 1.22 into 10 to the power minus 8 plus 4.6 into 10 to the power minus 4. So, that becomes J 8.02 into 10 to the power minus 8 f plus 4.6 into 10 to the power minus 4. So, like that you can also calculate if it is asked cross talk you will have to also find what is V f e by V s. So, that you will be able to do just by putting the formulas. So, this is all about frequency domain cross talk analysis. So, we have seen the coupling coefficients for capacitive coupling inductive coupling and the common impedance coupling. So, you see that cross talk it is a complex quantity it has a real part which is the lossy part and it also has a reactive part.

$$R = 1 K\Omega$$

$$M_{NE}{}^{IND} = \frac{1}{2} \times \frac{0.84 \times 4.737 \times 10^{-6}}{10^3} = 5.7 \times 10^{-10}$$

$$M_{NE}{}^{CAP} = \frac{10^3}{2} \times 5.17 \times 10^{-12} \times 4.737 = 1.22 \times 10^{-8}$$

$$M_{NE}{}^{cI} = \frac{1}{2} \times \frac{0.92}{10^3} = 4.6 \times 10^{-4}$$

$$\frac{\tilde{V}_{NE}}{\tilde{V}_S} = j \, 2\pi f \left(5.7 \times 10^{-10} + 1.22 \times 10^{-8} \right) + 4.6 \times 10^{-4}$$

$$= j \, 8.02 \times 10^{-8} f + 4.6 \times 10^{-4}$$

$$\frac{\tilde{V}_{FE}}{\tilde{V}_S} =$$

So, now we will move on to the time domain coupling which is actually today's lecture all about to find near end and far end in use voltages and currents for that actually ah frequency domain cross talk is a steady state and generally it is for generally it is for sinusoidal voltage excitations any arbitrary waveform can be broken as sinusoidal components that is true, but in transient what happens that is an interesting point. So, ah we know that in our clock or in our signal there are transitions. So, there we may be

interested to know what is the cross talk happening in those transitions. So, for any arbitrary time variation of the source what is the near end cross talk, what is the far end cross talk that is the subject matter of time domain or transient cross talk we can say transient or time domain cross talk. So, again we make the assumptions in the model the assumptions is similar to the frequency domain cases the first is only T M mode propagation through the line, then line is lossless, then homogeneous that means, the lines are perfect there are no losses and the medium in which the lines are there that is homogeneous. Now that means, you see with this assumption we are initially removing common impedance coupling later we will rest ah relax that assumption and we will include common impedance coupling. Then electrically short line electrically short line and the frequency is not very high that means, basically you can say less than 1 gigahertz this model will go. So, we know that phasor cross talk voltages are V ne J w is equal to J omega M ne V s J w and V fe this is frequency domain this is frequency domain we have already seen that .

this M ne M fe where M ne is equal to R ne by R ne plus R fe L m by R s. So, this was our condition. So, clearly this part is M ne inductive and this part is V ne plus M ne capacitive. Similarly, M fe is equal to minus R fe by R ne plus R fe into L m by R s plus R l plus R le R fe by exactly similar to M ne cap ah. So, this is M ne plus R fe R l C m by R s plus R l where this is M fe inductive and this is M fe capacitve. So, this is what we have already seen.

$$M_{NE} = \underbrace{\frac{R_{NE}}{R_{NE} + R_{FE}} \frac{L_m}{R_S + R_L}}_{M_{NE}^{IND}} + \underbrace{\frac{R_{NE} R_{FE}}{R_{NE} + R_{FE}} \frac{R_L C_m}{R_S + R_L}}_{M_{NE}^{CAP}}$$

$$M_{FE} = \underbrace{-\frac{R_{FE}}{R_{NE} + R_{FE}} \frac{L_m}{R_S + R_L}}_{M_{FE}^{IND}} + \underbrace{\frac{R_{NE} R_{FE}}{R_{NE} + R_{FE}} \frac{R_L C_m}{R_S + R_L}}_{M_{FE}^{CAP+}}$$

where

Now, we know that the term J omega in the frequency domain that translates to d dt in the time domain that means, J omega in the time domain it becomes d dt. So, the we can say that V ne t what is the time domain cross talk it will be the coefficient is same only d V st dt V fe t is equal to M fe d V st dt. So, that is all I have just got this result from here that V ne J omega is this. So, V ne t is equal to M ne d V s dt V fe is equal to V fe t is equal to M fe d V s dt. So, now, the equivalent circuit I of the receptor thing I can draw like this. So, this is our R ne this is our V ne t this what is this will be simply if you look at L m d I g t dt this is C m d V g t dt this is V g t dt. This is R fe this is V fe t that is all how I got this you see the frequency domain I have the thing, but here the nodes are not there. So, just you look at the circuit equivalent circuit for frequency domain there we have the voltage source was there J omega L m small l m L I g d c. So, that I have in time domain it will be L m into L is capital L m into d I g t dt and the current source that was J omega C m L V g d c. So, that I can write this this is the only thing. So, this is the equivalent circuit of receptor in time domain that is all. So, now, our job is we have got the equivalent circuit of the 3 wire transmission line. Now, we will see some typical cases of source excitation their d V s d t how it affects. So, that we will take up in the next class. Thank you.