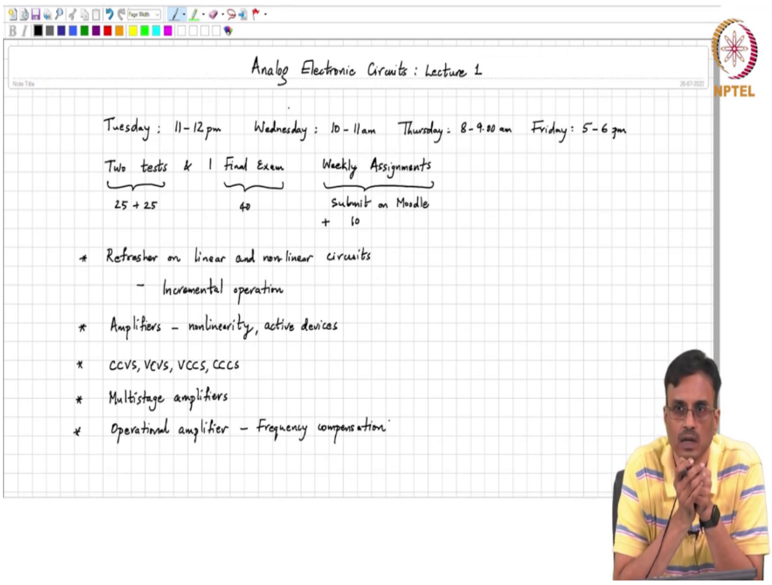
Analog Electronic Circuits

Prof. Shanthi Pavan
Department of Electronics and Electrical Communication Engineering
Indian Institute of Technology, Madras

Lecture - 01
Introduction – Linear and Nonlinear Networks

(Refer Slide Time: 00:18)

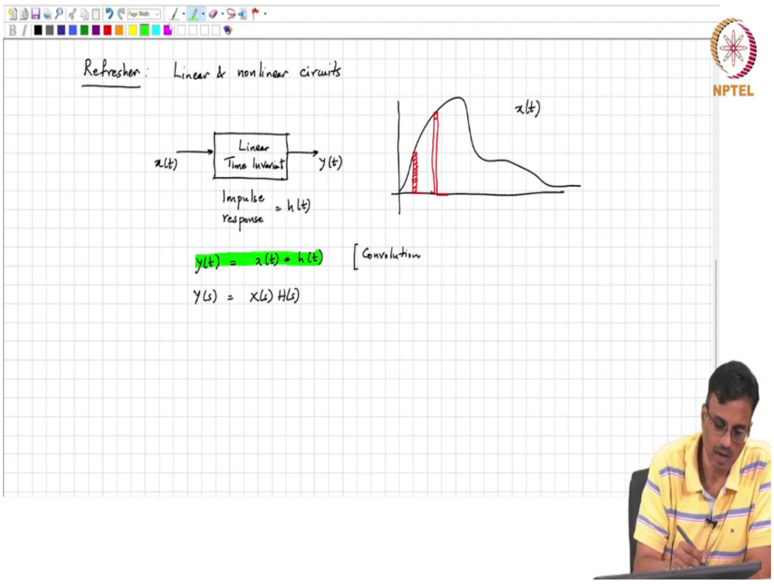


So, with the logistics out of the way. So, again welcome to E5310 Analog Electronic Circuits today in the introductory class I will go over what we are going to cover in this course. The outline of the course is as follows. We will first take a brief breather and refresher on linear and non-linear circuits and more importantly understand the notion of incremental operation.

Then we will learn about how to make amplifiers and we will see that nonlinearity is fundamental to making small signal amplification and we will see how the MOSFET comes about. Then based on our knowledge of active devices an example being the MOSFET, we will then look at making the four basic controlled sources, the current-controlled voltage source, the voltage-controlled voltage source, the voltage-controlled current source, and the current-controlled current source using transistors.

And we will follow that up with making multi-stage amplifiers and finally, look at the operational amplifier. In that process, we will learn about frequency compensation and how to stabilize a potentially unstable system ok. So, a lot of this material is most likely familiar to you because you have seen this in earlier courses, but in any case, we will start a fresh and go slowly and feel free to stop me at any time for questions. How many of you are MTech students here? 22 batch, ok, alright. So, very good.

(Refer Slide Time: 03:51)



So, let us get started, ok. So, you know in large parts of your prior curriculum in your you know engineering classes, you spent a lot of time learning about linear circuits and systems. Ok and not merely in your circuit's classes, but also in your courses on communication and you know things like that and control for that matter.

Where you have spent you know at least four or five courses learning about linear systems. When you learn signals and systems you are learning about Fourier transforms, and Laplace transforms which are basically applicable to the analysis of linear systems. When you go to linear integrated circuits or you know linear networks or linear circuit theory again you spent a lot of time learning about how to apply Laplace transforms to the analysis of linear circuits. Correct initial conditions and all this fun stuff.

Then when you learn went to communication you basically spend again a lot of time learning about Fourier transforms and you know what happens when a signal goes through a linear system and convolution and all this fun stuff. Ok. And finally, in control again you have learned about how to apply Laplace transforms to the analysis and you know the analysis of feedback systems where every block is linear. Correct ok.

And I hope all of you appreciate the fact that the only you know a linear system is perhaps the only one which is amenable to the analysis using transform techniques correct. So obviously, you therefore, the bottom line is that you spent a lot of time learning about linear systems and tools to analyze linear systems namely the Laplace and the Fourier transform, correct? But unfortunately, you know that the world is.

Student: Non-linear.

non-linear, I mean there is nothing called a perfectly linear element, it's only degrees of nonlinearity that vary, and therefore, it appears as if you spend all your time learning about systems that are linear and time-invariant, correct? But unfortunately, the real world is neither linear nor time-invariant at least you know the time variance apart to begin with it is not linear, ok.

And if a system is not linear none of the tools that you use alright. So, you know, for example, the Laplace transform. Why do you think you spend so much, I mean what is so great about the Laplace transform and why is it so useful? Why is it useful? So, the key attribute of a linear system is that if you have a system that is say and for simplicity let us assume this is also time-invariant.

So, this is linear and time-invariant. Then if you apply an arbitrary input x(t) to the system the output is y(t) and you can always think of y(t). So, let us say this is some x(t), and if you think of the input as a series of thin slivers like this for example, here is 1. So, you can break this up into a bunch of thin slivers like that and each sliver can be thought of as?

Student: impulse.

You can think of it as a small impulse and if you know the response of the output response of the system to an impulse then because the system is linear you know its response to a.

Student: Scaled impulse.

The scaled impulse is correct. And because the system is time-invariant if you delay the input.

Student: The output is also delayed.

The output is also going to get delayed by the.

Student: Same amount.

Same amount. So, basically, if you know the response of the system to an impulse, the output is simply seen to be given by, how will you find the output?

Student: Convolution.

Is simply the convolution of this is provided.

Student: LTI.

It is LTI. But even in an LTI system, there is important that the initial conditions must be 0. So, fine. So, why is a transform technique useful?

So, the key point is that in the transform domain Y(s) is simply X(s) * H(s). In other words, in the transform domain convolution becomes.

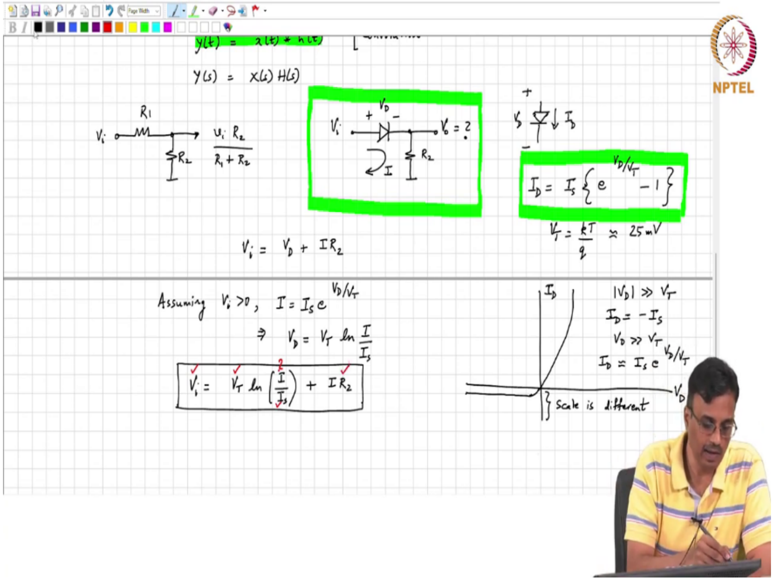
Student: Multiplication.

Multiplication. You cannot do this since this is not valid. So, since this is not valid for a non-linear system, a transform domain what do you call tools become inapplicable. And therefore, the analysis of non-linear systems and circuits is fundamentally more difficult to do than,

Student: Linear system.

A linear system. Ok and as a case in point let me take an example.

(Refer Slide Time: 10:46)



So, this is R_1, this is R_2, this is V_i. What is that output?

It is $\frac{V_i R_2}{R_1 + R_2}$, right? It is so, obvious that you may think that the circuit is all I mean this question is almost insulting alright.

Now, you know this is perhaps the simplest linear circuit that I can think of. There is no memory, there is only two components, right? So, if you want to think of the simplest non-linear circuit what do you think you will do?

You replace one of these elements with some non-linear element that you know. So, what is the simplest nonlinear element that you know?

Student: The diode.

The diode is ok. So, the diode, let us say I just put it there. So, this is R_2 and this is V_i. What is the output voltage? How do we figure this out?

Student: Because of the conditions.

What conditions?

Student: If V_i is greater than 0.

No, by the way what is the I V relationship for a diode? This is I, this is let us call this V_D and this is I_D. How is the current related to the voltage?

$I_D = I_s (e^{VD/VT} – 1)$, ok, and what is V_T?

$V_T = kT/q$. Where k is Boltzmann's constant, T is the absolute temperature and q is the charge on an electron and this is approximately 25.8 millivolts at room temperature. but you know for our purposes we will simply use a round number 25 millivolts ok. And if you are not happy with this, then I am going to say well we cool down the room until V_T = 25 millivolts, ok alright.

Now, the question is, how do we figure out what V_0 is? This is the IV characteristic of the non-linear element. So, what do we do? How do we figure out what the output voltage here in this circuit is?

Student: We can apply KVL.

That is alright. As electrical engineers, right? the only thing we know is to apply.

Student: KCL

KCL and.

Student: KVL.

KVL alright. That is what we are going to do. So, we do not know anything. So, we are going to say this current in the loop is unknown, and that is some I, ok. And write Kirchhoff's voltage law which is KVL. So, V_i is nothing but the voltage drop across the diode plus the voltage drop across the resistance.

So, that is basically $V_i = V_D + I R_2$. Does that make sense? Ok now V_D unfortunately is not explicitly known in terms of I_D, correct? V_D is a non-linear function of I_D. So, what comment can we make if I_D is given by this equation? what comment can we make about how is V_D related to I_D?

Well, a couple of observations first. It always makes sense to draw a picture when you see an equation. So, if I plot V_D on the x-axis and I_D on the y-axis how does that picture look? For

V_D which is large and negative. So, V_D being large and negative basically means what? $|V_D|$ is, by the way, what is the meaning of large?

When I say V_D is large what does it mean?

Student: That means, by which function we are comparing which means here we are comparing with V_T.

Correct.

So, very good. So, basically please note that this notion of large, small, you know thin, fat all these are relative terms, right? It does not mean that you know 25 milli volts is a small value, of course, it is small when compared to 200 volts, but it is very small when compared to 2 microvolts ok.

So, similarly, when you say a large V_D, it must be in comparison with something else, and that something else depends on context correct? And in this context what comment can we make about V_D? When you say a large negative V_D what does it mean?

It must be with respect to V_T?

So, therefore, if for V_D absolute value of V_D much much larger than V_T. What comment can we make about the diode current? You can ignore which part? You can ignore the exponential term and therefore, I_D becomes nothing but $-I_S$ ok. So, you draw something like this and if you want to see I_S you know on the same picture as the for when $V_D > 0$, the only way to do that is to observe that this must be a different scale ok.

Now, if you go and pick up a diode in the market, I mean you know typically these diodes will have the reverse saturation currents of the order of maybe a few 100 pico amps ok. And so, when $V_D = 0$, what is the current?

It is 0 ok. And when V_D is much much greater than V_T what comment can you make?

It is an exponential function ok. And $I_D = I_S e^{(VD /VT)}$, correct? So, first things first. Staring at this picture of the circuit can we figure out whether the $V_D > 0$ or $V_D < 0$? If V_i is positive, do you think $V_D > 0$ or $V_D < 0$? It is.

Student: Greater than 0.

It is greater than 0. That is apparent I think, right? So, then which part of the equation will you use? Use the exponential part. So, assuming $V_i > 0$, it follows that $I = e^{(VD/VT)}$ where we neglect the negative one. And therefore, what comment can you make about V_D? So,

$$V_D = V_T \ln ln \left(\frac{I}{I_s}\right)$$

It makes sense people? Ok.

So, now, therefore, you just plop this into our equation because voltage law equation here. So,

$$V_i = V_T \ln ln \left(\frac{I}{I_s}\right) + IR_2$$

So, what is the known what are all the known quantities here and what are unknown?

Which all are known V_i is known or not? This is the applied voltage we know. What about V_T?

Student: Known.

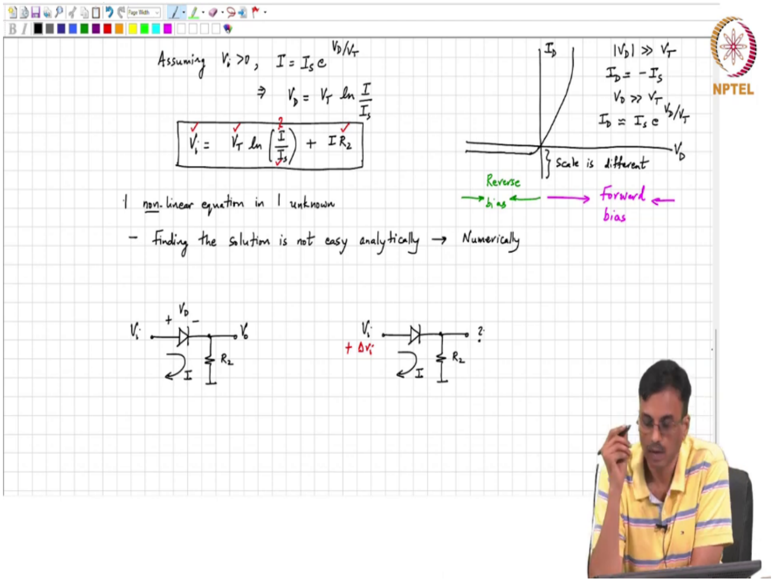
Known, I_s.

Student: Known.

Its known because we know the property of diode I is unknown, what about R_2?

Student: Known.

(Refer Slide Time: 20:48)



Known ok. So, clearly this is one non-linear equation in one unknown ok. Unfortunately this is a difficult non-linear equation to solve is a transcendental equation. And therefore, how do we go about what do you propose that we do to go and find I? Yeah.

So, I mean you know you can pick your favorite numerical algorithm to find the solution, right? So, in other words, finding the solution is not easy analytically, but then we say well the solution to this is that you find it numerically given you know V_i, V_T I_s and R_2. You go and you can go and go to your favorite mathematical package you know octave or MATTLAB or whatever.

Plop these numbers in and the package will solve the equation for you. And you will basically get the current height alright. and by the way this region of operation of the diode what is this region of operation called?

Student: Forward bias.

It is called forward bias and this region is called reverse bias. So, to summarize our discussion so far even the simplest non-linear network that one can think of where you have taken that trivial R_1 R_2 network and replaced one of the resistors with the simplest non-linear element that we know namely the diode already we can see that finding even something as simple as the loop current, right?

Which we see which we are which we did by inspection when we looked at that R_1 R_2 network has already become quite complicated and we need to resort to the use of MATLAB to basically or some kind of similar numerical package to go and actually find the current, I ok. Now, let us say you have gone and done all this hard work. So, we have gone and done all this hard work and once you find I, how will we find V_o?

Student: I x R_2.

I x R_2 correct. So, let us say we have gone and found this network a solve this network completely. Now somebody comes and tells you, well I am going to change the input voltage by a small amount, and now can you tell me what the output voltage?