Analog Electronic Circuits
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Lecture - 01
Introduction to analog circuits, introduction to the diode

Hello everyone, this is the first lecture for the MOOC course on Swayam, on Analog Electronic Circuits. And, this course is meant for undergraduate students maybe in their second or third year. And, the let me first start off by discussing the contents of the course. So, the content of the course; the primary content of the course is to learn about amplifiers.

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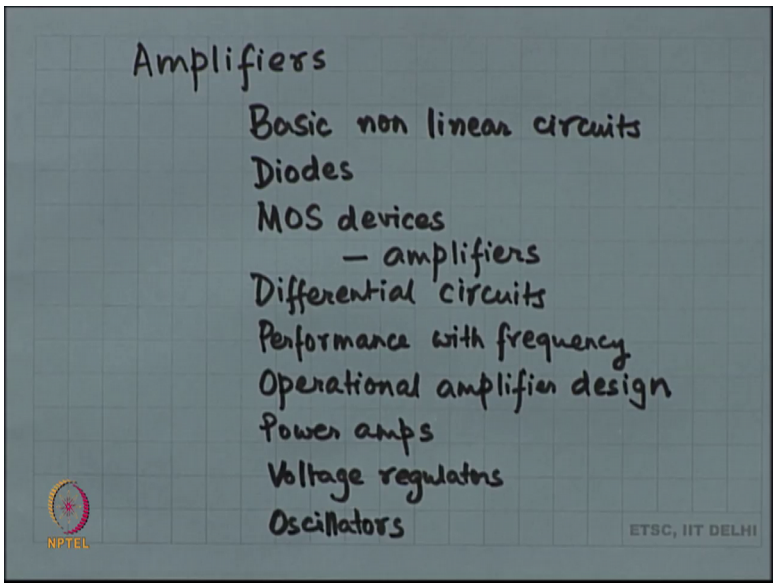

And as part of this endeavor we are going to start with basic non-linear circuits including circuits that involve the use of diodes then we are going to start using MOSFETs. So, with MOS devices we are going to make a very basic amplifiers single transistor amplifiers; common gate common source common drain amplifiers, then we are going to start making 2 transistor multi transistor amplifiers.

Then we are going to study differential circuits followed by the effect of capacitance. So, the performance of these circuits with frequency and then finally, we are going to work on the op amp that is we are going to learn how to design an operational amplifier. In this

course we will also try to cover a little more specialized topics like power amplifiers, voltage regulators and if time permits oscillators.

So, this is a very brief outline of the content of this course and to start with in today's lecture what we are going to discuss is what are amplifiers and what is the meaning of our course title. So, this is going to be my objective number 1 ok. So, to start with the title of the course is analog electronic circuits. Now you have all heard about digital circuits and analog circuits are the antonym of digital circuits.

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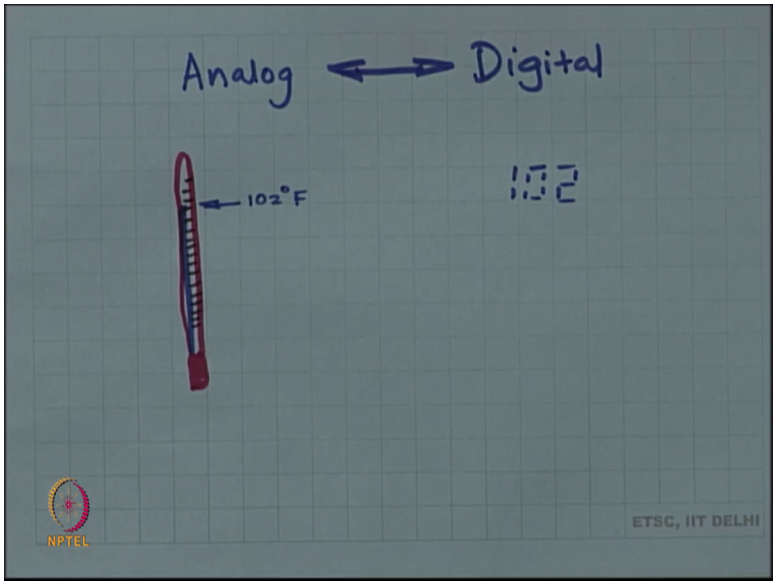

Now, the natural question is if the world is going digital; why should we study analog circuits at all? And the answer for that is that indeed the world is going digital, but our world the world around us is all analog. So, to give you an idea the picture that you see is analog when you see something, it is analog when you hear something it is an analog perception.

When you smell something it is an analog perception all our perceptions, are analog, but when it comes to sending information to a computer for further processing; you would like to send it as in a digital format. So, in between there has to be a circuit in between this analog world of ours and the digital computer. There has to be a circuit in between that converts the analog stuff takes it, senses it, amplifies it and converts it in to digital and then hands it over to the digital circuitry that processes, right.

So, this is this is the basic idea; so, the difference between analog and digital according to me the easiest example is that of a thermometer. So, if you think of a mercury thermometer; so, this is your standard mercury thermometer and on the side you have these graduation marks right and if the column of mercury reaches a certain height then you read out what the temperature is. So, the column of mercury reaches a certain height and you have read out that oh the temperature is whatever is written over here 102.4 degrees suppose ok.

So, this is an analog system; a digital system would not have this column of mercury instead a digital thermometer is just going to say oh the temperature is 102.4 degrees and it would be written digitally on the thermometer itself. So, the difference between analog and digital is that a digital system is discrete, it can do 102.4 it can do 102.3, 102.2, 102.1, 102; it cannot do 102.25 where as in an analog system; this could have been slightly more and it is up to you to make that reading.

If you can read it as 102.25 then great; if you cannot it is your problem right. So, in analog system naturally has precision whereas the digital system is in precise right; it is discrete values ok. So, this is the basic difference the digital system is going to give you this reading. The same thermometer digital thermometer will read you 102 and analog thermometer will have to read according to the column of mercury ok.

So, everything around us is an analog perception whereas the computer is digital which means that every photograph has to be digitized and then processed ok. So, in the typical system what do we have? In a typical system we have first going to have a sensor.

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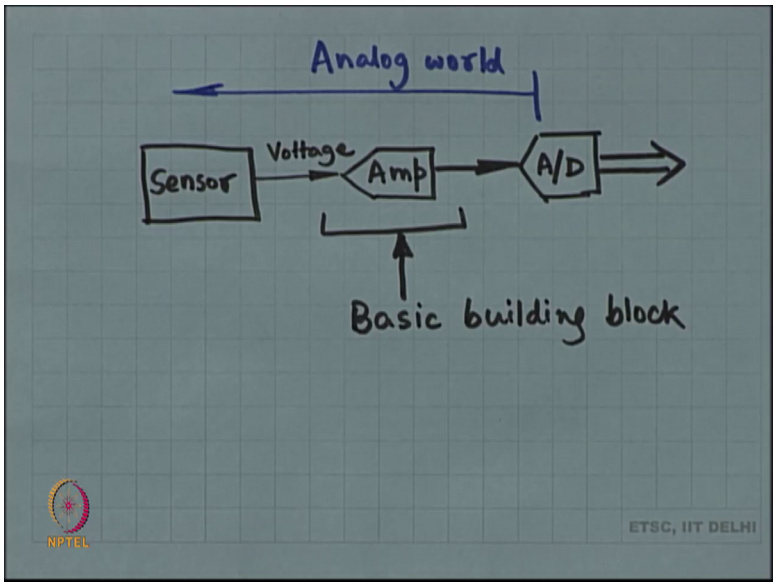

So, let us think of a photograph. So, a photograph will first have a sensor I have to take a photograph and digitize it. First you have to have a sensor this sensor is an array of pixels in case of a photography right lots and lots of pixels.

All these pixels are going to produce voltages which are proportional or which depend on the amount of light that has fallen on them. So, this sensor is going to produce a voltage. So, I am saying a voltage, but in case of an array of pixels it is a set of voltages alright and what is the first thing that you have to do? The first thing that you have to do is to make sure that the amount of noise in the system does not corrupt what has been sensed ok.

And to do that you first have to amplify this, you have to first increase the value of the voltage. So, that in a in such a way that the noise in the system does not corrupt the individual voltages and for that reason we are going to use an amplifier. And then what are you going to do? Then you are going to use an analog to digital converter and then you are going to take the digital samples and store it in memory or do whatever else that you want to do ok.

Another example is voice suppose I am talking not through the internet I am I am just talking in a class and there is a microphone over here. So, my speech is going straight to this microphone then the microphone converts the speech into a digital signal. So, this microphone is catching the speech from voice right its and what does it do? Inside the

microphone there is a carbon is packed in and according to the sound pressure level the resistance of the microphone changes right and that is your pick up.

So, eventually what happens is that if I a push a constant current through the microphone; then the resistance is changing that creates all voltage right. So, the voltage changes ok; so, this voltage has to be sensed. So, you got my speech then the speech goes to the microphone the microphone effectively is going to produce a voltage right this voltage goes through this long wire and in my pocket there is this battery operated amplifier right.

This battery operated amplifier is going to convert this voltage first it is going to amplify it then it is going to digitize it, then it is going to convert it in to an RF signal right and over the radio frequencies it is going to communicate to the sound system that is far away ok, but that is a digital signal. So, this is the general idea this amplifier happens to be a basic building block ok.

Why is this amplifier; is the basic building block; because right after the sensor you always need that amplifier; you cannot not have that amplifier over there, ok. In fact, what happens is that there is one amplifier and then there is a reasonable amount of signal processing in between the amplifier and the A to D converter, then the A to D converter converts into digital and finally, there is a large amount of signal processing at in the digital domain.

But it is much more economical to have a significant amount of signal processing in between the amplifier and A to D converter and that is also an analog circuit ok. So, this is the analog world and in the analog world; one of the most basic building blocks is the amplifier alright; one more example a classic example is the hard drive of a computer.

So, the hard drive of a computer there is a platter let me write.

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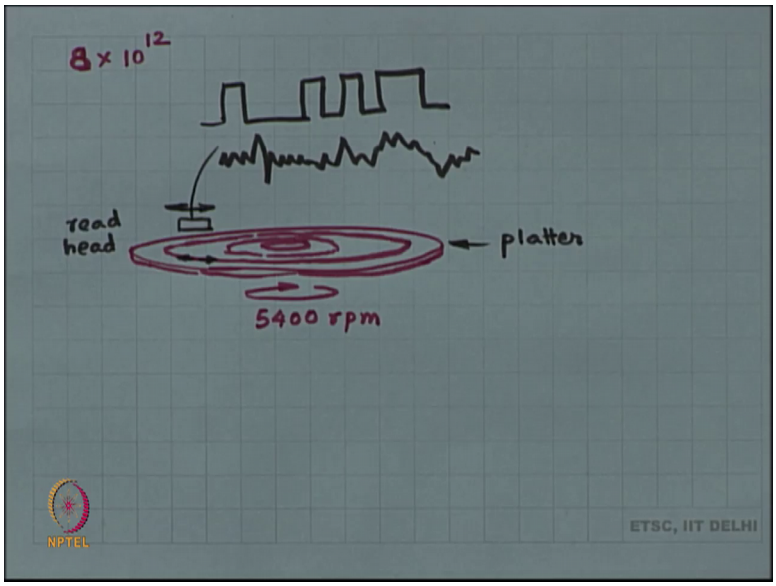

I do not know if you have seen the insides of the hard drive, but his flatter and if you think of a 1 terabyte hard drive; it has 1 kilo means 1000 mega is a million, Giga is a billion, Tera is a trillion, right. So, 1 terabyte refers to 1 trillion bytes. So, 1 trillion bytes 1 into 10 power 12 bytes and each byte is made up of 8 bits stuff that you know already.

So, there are actually 8 into 10 power 12 bits; now on a magnetic hard drive these bits are stored as little magnets that either point to the north or they point to the south alright; is that understood? So, these 8 into 10 power 12 that is a gigantic number. So, many little magnets have been organized into tracks right, they have been organized into tracks around the spindle of this platter right.

And each magnet is tiny it is a tiny particle and that particle is residing if either pointing; this way or its pointing the other way depending on whether it is a 1 or a 0 ok. So, all of these are on this tracks now this hard disc is spinning around at an incredible speed right. So, this is going round and round at let us say 5400 rpm how many revolutions is that per second ok.

So, rpm is revolutions per minute think about it is spinning 90 times per second that is incredibly fast it is spinning right. And you have to read from this while it is spinning; so, what is done is there is a magnetic head and that magnetic head comes and flies on top of this platter, very close to the platter it flies at the right place flies in on the right track right.

Suppose it has to read a certain file you have to read this jpg file from the hard drive you have to access it. So, the computer knows way on which track this jpg file is; so, it sends the hard disk read head. So, this the read head this is your platter. So, the read head has to align itself to the correct track or the correct cylinder in the in the words of the hard drive with this is called a cylinder.

So, it goes to the right cylinder right correct track and then sits; it flies right on top because it has to fly why does it have to fly, because if it touches the spindle and the spindle is revolving at an incredibly fast speed you are going to get a scratch on the spindle and there goes everything. So, it cannot touch it has to fly very close to the spindle maybe a micron about the spindle right.

And it has to sense all of these magnets that are going underneath it the orientation of all of them ok. So, in variably if you look at the voltage coming out of this right; it does not really look like I mean you would wanted to look like a series of 1s and 0s right, you think it would look like this it does not look like this at all. In fact, it has no resemblance to 1s and 0s at all it probably looks like some noisy signal ok.

And this signal has to be amplified then you have to do a significant amount of signal processing to work out exactly what those bits were or that were on the platter that were residing on the platter. So, each bit is actually interfering with the next bit. So, when you are trying when you think your reading 1 bit you are not really reading 1 bit you are reading 10 bits at was you are reading many many bits at the same time.

So, each voltage sample over here is the effect of many different bits. So, if you think about it is not something very straight forward and digitizing the signal makes no sense at all ok. So, you have to do a large amount of analog signal processing with this particular voltage to obtain finally, you want to obtain this digital signal, but what you get is this right you have to do an incredibly large amount of analog signal processing to arrive at this from this ok.

So, this is just to give you an idea of the importance of analog circuits and the flavours of analog circuits that we are going to talk about we might not be talking about this kind of analog circuit in this course, but I am just trying to point out that these are examples of classic analog circuits ok. Next we are going to start with the amplifier.

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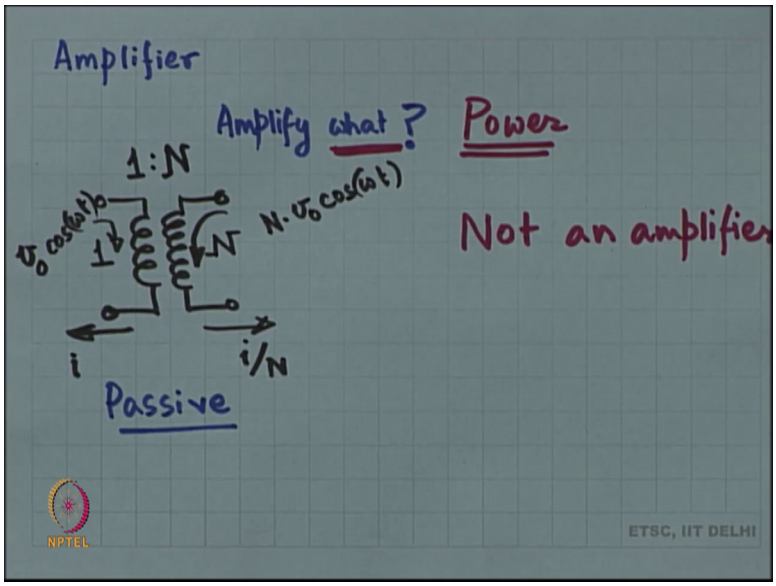

Now, when I talk about an amplifier what does it amplify? For example, I mean I want to illustrate the question.

Let us see if you understand the question; think of a transformer suppose this transformer has a turns ratio of 1 is to N I apply a voltage v naught COS omega t, on the primary side on the secondary side the voltage I will get is N times v naught COS omega t is this transformer an amplifier; is it an amplifier? Is a transformer an amplifier, do you think it is amplifying anything?

Is it? Well the voltage is increasing and in v naught COS omega t on the primary side on the secondary side you had N times v naught COS omega t the voltage is increasing, but what about the current? At the same time, if I had some current i over here the current on the secondary side would be i by N right. So, if I had on the primary side if my current was I on the secondary side my current is I divided by N which means that effectively.

If I increase the voltage N times the current is decreasing N times that is happening because power is being conserved right energy is being conserved; there is no loss in this ideal transformer great. So, whatever power you are throwing into the transformer is coming out of the transformer ok. So, in this case we say that the transformer does not amplify anything; this is not an amplifier ok.

The transformer does not amplify anything why? Because whatever power you throw at the transformer, at the input it comes out at the output; if at all the output power will be less than the input power it would be more than the input power was alright. So, the transformer does not amplify anything even though the voltage on the secondary side increases right, it does not amplify anything the transformer is passive ok.

So, what does an amplifier amplify? Now I come back to the question now that I have illustrated why I am asking the question I come back to the question, when we are going to talk about an amplifier what do we need to amplify? The voltage; no because a transformer can also increase the voltage right, transformer is not an amplifier ok; so not voltage current? No, right because the transformer could also have increase the current you just switch the primary and the secondary.

You call the N side as the primary and the one side as the secondary and you are done right you can you can increase the correct at the cost of decreasing the voltage and it still passive. So, it does not increase the voltage an amplifier is not just something that increases the voltage. An amplifier is not just something that can increase the current because these can be achieved with a transformer 2, an amplifier will amplify will amplify? Power.

So, the answer to this question is power when I say amplify what? You have to amplify power an amplifier has to amplify power alright. And then you are going to say that you have learnt a lot of physics and you know my class 11 class 12 and so on and so forth. And the law of conservation of energy is the guiding principle of the universe and there is no way to violate the law of conservation of energy. So, what is this gentle man talking about? I mean he is saying that an amplifier is something that amplifies power this cannot be right.

Because nothing there is no way to amplify power you cannot I mean if you have a system and I through some power at it. Then you cannot get more power out of it if there is there us no way that it will produce more power than it was given right. Because you have to also follow the law of conservation of energy I agree you have to follow the law of conservation of energy there is no way out.

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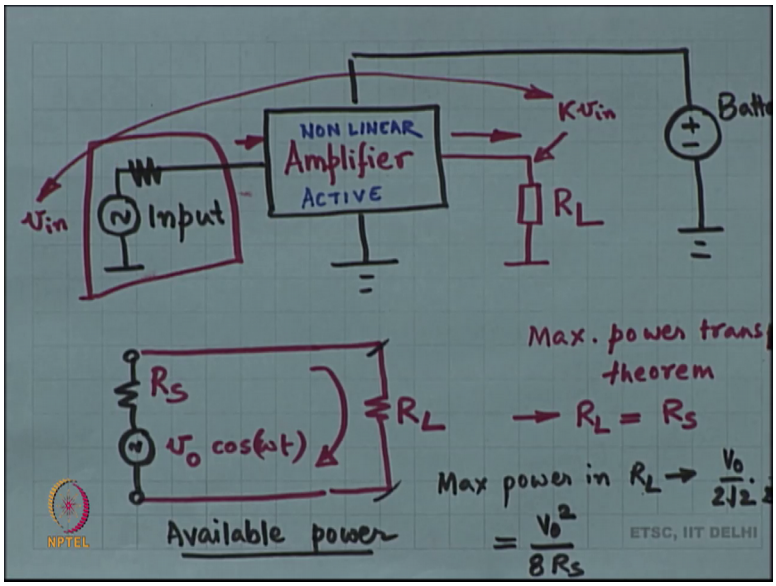

So, what we normally have think of in is a black box; think of a black box and in this black box I am willing to give you extra power from a battery ok. There is a battery take as much power as you want from the battery. Now I am going to give you an input; so, here I am showing a sinusoidal voltage source, but this is really a sensor right and when we say that it is a sensor, the sensor is going to have to some source resistance.

Because if it does not have a source resistance then you can use that voltage source directly and it will produce whatever power that you ask it to produce. Whereas, if you have a source resistance associated with the sensor then the amount of power that that particular voltage source can produce is limited am I right? What am I talking about?

So, if you have a voltage source with let us say v naught COS omega t is the voltage source and let us say this is R S is the source resistance. Then what is the maximum power that can be generated that that can be produced by this voltage source. So, the maximum power is drawn by a load the maximum power transfer theorem you know this is recapitulation right.

So, maximum power is drawn by R L; when R L is equal to R S if R L is equal to R S then the current is v naught COS omega t by 2 times R S and therefore, the power in R L is going to be square of that times R L and then you have to take the RMS which gives you a by root 2. So, the maximum available power; so, what is the what is the power in R L finally?; v naught COS omega t by 2 is the voltage across R L ok.

So, so if I just take the amplitude right and I do not want to keep writing COS omega t then COS omega t square; I can do RMS right let me just do phase or and RMS and so on. So, the phasor for this is going to be v naught by root 2 ok. So, the volte the phasor voltage across R L is going to be v naught by 2 root 2 and the phasor current is going to be v naught by root 2 by another v naught by root 2 and then 2 R S. So, v naught by 2 root 2 times R S is the phasor correct.

And effectively that gives me V naught squared by it R S where V naught is the amplitude if V naught had been the RMS already ok. So, if your amplitude is V naught, then the maximum power in R L is v naught squared by 8 R S; so, this is also called the available power ok. So, the available power in that sensor is limited when I say that the available power is limited then that means that this R S is some finite value.

Because, if R S had been equal to 0, then the maximum available power can be in finite you can you can get whatever power you want out of that ok. So, that is what I wanted to pointed out and it all comes from the maximum power transfer theorem alright. So, this is my setup my setup is that I have a sensor which comprises of a voltage source in series with a source resistance. And this is going to go to a black box, this sensed voltage is going to go to a black box.

This black box is going to be powered externally with a battery and you are allowed to draw whatever power you want from the battery. Now the black box is going to output voltage on to a load or it is going to output power on to a load right; this load need not have anything to do with R S now ok; these 2 are now unrelated right. If this black box has not been there then maximum power would have been transferred if R L would be equal to R S.

But right now they are not related at all because I have put a black box in between. Now the question is that this available power at the input; so, the maximum power that I can draw from the input; this black box can draw a maximum of v naught squared by 8 R S over here that is the absolute maximum power that this black box can draw from the sensor.

But with the help of the battery can I produce any arbitrary power and drive it on to the load? Ok if I can then this is called an amplifier ok, it is amplifying power at the end of the day it is amplifying nothing I mean there is there is no amplification or at the end of

the day I mean power is conserved. At the end of the day its drawing power from the source, it is drawing power from the battery and it is throwing power out into R L and it is also going to heat up on its own.

So, you have to have the law of conservation of energy with all of these things; it is drawing power from the source, it is drawing power from the battery, it is throwing power out of to the load and it is having self heating ok. So, you do the law of conservation over here at the end of the day; it is not really amplifying power as much. However, if you look at the signal the signal is coming from the sensor right; I want a scaled version of the signal. So, if this is v in; I want the scaled version of the signal K times v in over here it is not a constant voltage ok.

Some I mean K can be positive, negative, large, small whatever you want K some value. So, this is the relationship of the amplifier and at the end of the day it would have therefore, amplified power I mean K squared by sorry this is an amplifying voltage by a factor K right.

But the current is not really going down in this case right the current over is K v in by R L and that is the output current; the voltages K v in right which means that the output power is K square v in by R L ok. The maximum available power was something else something related to R S; R S and R L are unrelated R S can be very large it does not matter. So, even though power was not really available from the source with the help of you know battery, you would have provided power to the load such that input output relationship is maintained ok.

So, that the entire idea of the amplifier is that clear ok? Now to make such an amplifier will you be able to make it with the passive elements? This is a how many ports are there in this 1 2 3 ports right is it is it if I would you be able to make a 3 port network with passive circuit elements right; basically resistors inductors capacitors do whatever you want will you be able to make the circuit is it possible? Yes? No? Ok.

Yes, you cannot make such a circuit with passive elements using resistors inductors and capacitors it is not possible to make this amplifier. Why not? Why not? Because the battery is going to produce power is has able to produce power at DC ok. So, if this circuit is passive and DC power will remain DC at the output, it is not going to be translated to the frequency of the input voltage. The input might be at some other

frequency right; it might be accepting frequency omega I want the DC power to be translated to frequency omega.

And linear circuit elements do not allow such things to happen. So, think about it I gave you the answer, but think about it might an answer is I give you a compact answer, but think about it you might have not understand it in the first shot; you know rewind ask yourself again take clues, take hints from what I just said that the DC power is never going to be translated into any other frequencies.

Suppose the frequency is at omega right omega power is going to be fine it is going to remain at domain and if the circuit is linear right; we are talking about linear passive elements like L C and R as long as the circuit is linear and passive input power input frequency will get is fine will remain; you will get the same power or less at the output and whatever power is being produced by battery will remain at DC ok.

So, think about my answers rewind reverse a few times before you convince yourself that this amplifier cannot be made at all using components like L C and R only alright. So, what do you need? As I said you cannot use L C and R only what do you need? Can you use other passive components? Can you can you make this amplifier with the help of a diodes? Can you? The answer is no once again. So, as long as you have passive components you cannot do it ok. Not just linear this box has to be made using active components, it is not sufficient to have only pure passive elements in this box ok; you need to prove this to yourself think about it.

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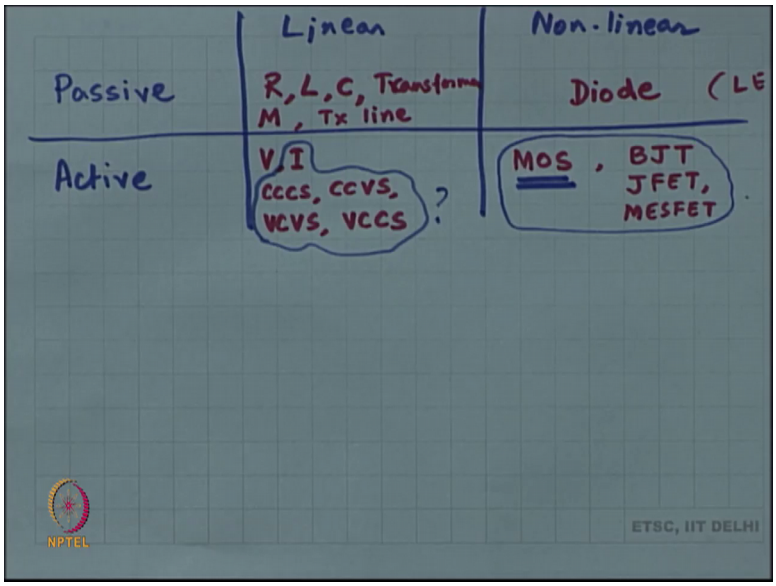

So can you fill up this table linear passive components are what? R, L, C, transformer, mutual inductance right these are all linear and passive. So, transmission line these are all linear and passive elements non-linear passive elements; give me an example, diode great; active? Linear active elements do you know any elements that are linear and active? Example, voltage source ok, current source these are 2 main things right.

Voltage source and current source and you have the control sources. So, you have CCCS, CCVS, Voltage Controlled Voltage Source and Voltage Controlled Current Source ok. Now course these 5 elements these 5 elements we do not really know how to make them right, you might know how to make a voltage source right? You like a battery, you can buy it in the market volt battery is a voltage source, but current source we do not yet know how to make current sources and all these controlled circuit elements are all are they have been discussed in your circuit theory class in other network theory classes and so on.

However, I am sure right now you have no idea how these components can be made ok. So, we will have to live with only the voltage source as a linear active element ok; then come the non-linear active elements any ideas any names that you have? Any names to have for the non-linear active elements; ok so the MOSFET and that is a going to be a primary subject matters of course, understand how it behaves and like the MOSFET there is another transistor called the bipolar junction transistor.

And then again there are you know other lots of other different kinds of transistors there are J FETS there are all kinds of other MESFETs all kinds of other devices exist and all of these are non-linear, but active devices great. What about the LED the Light Emitting Diode; what is it? Active passive it is a diode light emitting diode is non-linear, but it is a passive element it just a diode alright.

So, this covers the spectrum of a non-linear linear components and going back to this discussion of the amplifier right. If you had linear circuit elements frequency would be conserved in terms of power which means that the amplifier cannot be made with only linear elements, it has to have non-linear elements. So, you need non-linear and at the same time you need active circuit elements.

So, we have to work with devices in this last bracket right in particular in this course we are going to work with the MOSFET the BJT used to be used a h used to be the subject matter of this course; however, the BJTs has been phased out. The BJT has been phased out of almost all analogues of circuits except maybe 1 or 2. So, I am my feeling is that you can study the BJT by yourself if required; in general it is not going to be required is this ok? Can we move on?

So, the first circuit element that we are going to study in this course is the diode.

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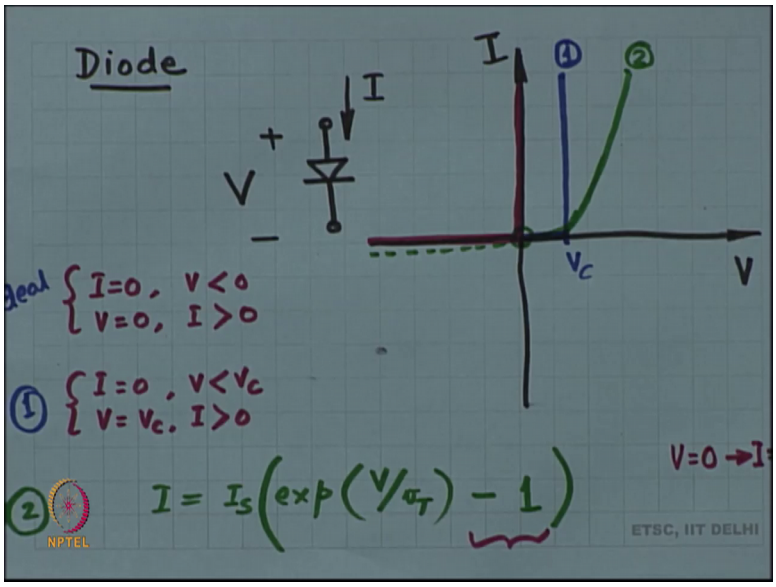

And this we will start from the symbol of the diode ok. So, diode is made out of a p-n junction all of that is there we are going to bother about it; however, if the current through a diode is I and the voltage across it is V; then V and I have a certain graph what does that graph look like? Do you know? I am sure you know that.

So, an ideal diode a diode that I would really like to purchase, but it is not available in the market, would have a characteristics that looks like this red curves. And you cannot really see it because it is merging with the axis. So, it is going along the negative x axis and the positive y axis that is when V is negative, I want 0 current and when V is positive I want infinite current that is when positive V cannot exist because the current through that becomes infinite.

So, current can go only in one direction and when it goes when the current goes in the forward direction then the voltage across the diode is 0. This is the one diode that I would like to purchase from the market; unfortunately the device manufacturers are unable to give me this device. In fact, we just cannot make it; in fact, they have gone so, far as to claim that this particular device cannot be made by anybody and they are never ever going to be able to make such a device; instead the device that we are going to give us has some non idealities some small imperfections and ok.

So, what are those imperfections? Number 1 imperfection is that it starts conducting not at 0, but at the voltage close to 0. So, there is a non zero any voltage over here non zero cut in voltage. So, this is called the cut in voltage let us call it V cut. So, in which case the model for the diode would have looked like that. So, it could merge with the x axis as long as voltages where below V C and above V C, you cannot apply a voltage because any volt the current would become infinite right.

So, it would be on would not have any drop above these ok. So, this is at the first level of abstraction; then they say the device manufacturer say that no they cannot give me this either. They are going to do one more round of abstractions right and they are going to the next level of abstraction is something that rises above these, but not particular it rises to right and then the device manufacturers further go and say that no even this is not possible.

What they are really going to give is something that also fall a little bit. So, my figure over here is exaggerated that little bit that I have shown is actually much smaller it falls a

little bit below the x axis ok. In fact, there were few device manufacturers who said that let us try making this perfect and so on and so forth, then the circuit theory guy came and said that no you cannot do it you have to pass through the origin ok.

So, I will come to that; so the first level of abstraction the red curve is what the red curve can be mathematically expressed as I equal to 0, when V is less than 0 and V equal to 0 when I is more than 0. So, this is the first graph the first abstraction this is what I wanted to buy; this is the ideal diode. The next level of abstraction is let know I cannot do V equal to 0 I will do V equal to V C when I is greater than 0, but for V less than V C; I will be equal to 0 this is the second one.

And then the third one; what is the third one? The third one says I mean the device manufacturer. Finally, says that no I cannot make all of these things this is all discontinuous and so on, whatever I make its going to be some continuous function and he says that I will give you I equal to some constant, some scaling constant times some exponential of V by V T here V T is K T by q ok. So, this is a what the device manufacturer wanted to give.

The came the circuit theory expert he said that; no you cannot make this it is not possible to make this, you have to make you can attempt to make this. Why is that? Why did the circuit theory man say this not the device expert? This extra minus 1 had nothing to do with the device expert, the device expert could not really measure that minus 1 right e power V by V T was so large that he could not measured the minus 1.

The circuit theory expert came and said that that there has to be a minus 1, but then otherwise there you are doing something wrong. Why? Why does it have to be there? I mean we are in a circuit class; so we understand circuit theory that the assumption. Why? Why does the minus 1 have to be there? Because at V equal to 0, I has to be equal to 0, if it is not equal to 0 then the device can produce; the device can generate power and this is a passive device ok. So, that is why that minus 1 has to be there by I mean you have to put that minus 1.

If you want to work close to V equal to 0 ok; so this is these are the abstractions of the diode. Let us stop here and in this class all the first we discussed the basic course outline right? Very briefly we discussed the basic course outline and then we discussed different

examples of a analog circuits. The thermometer right and how the amplifier is a basic building block, some analog signal processing was discussed with the hard disk platter.

Then we started working with the big question amplify what? The answer to that is power; the transformer is a passive device it does not amplify. Then we discussed the strategy to actually amplify power, we are not really amplifying, you are not really violating the law of conservation of energy. You are supplying power from a battery and supplementing, but effectively you are amplifying power between v in and v out ok.

We discussed the passive devices, active devices and the amplifier has to be made with non-linear and active components. And finally, we started our work with the diode right, we discussed different models of the diode and in the next class we are going to work with diode circuits.

Thank you.