Switching Circuits and Logic Design
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Lecture - 47
Digital-to-Analog Converter (Part I)

So, if you recall our discussions over the last few weeks, we have been discussing the design of digital circuits specifically both combinational and digital, combinational and sequential. Now, the thing is that the world we live in here most of the signals that we see around us they are not digital in nature rather they are continuous or analog that we call it. Let us take some example, take the example of temperature, pressure, humidity, light intensity, so everything through which we interact with the environment they are continuous in nature. And there are many applications many systems which directly interact with the environment.

So, we discuss now some devices or building blocks using which we can interface digital functionalities or digital systems that you already have seen how to design with the so called analog world. So, our first lecture in this regard is related to something called digital to analog converter or DA converter we call in short.

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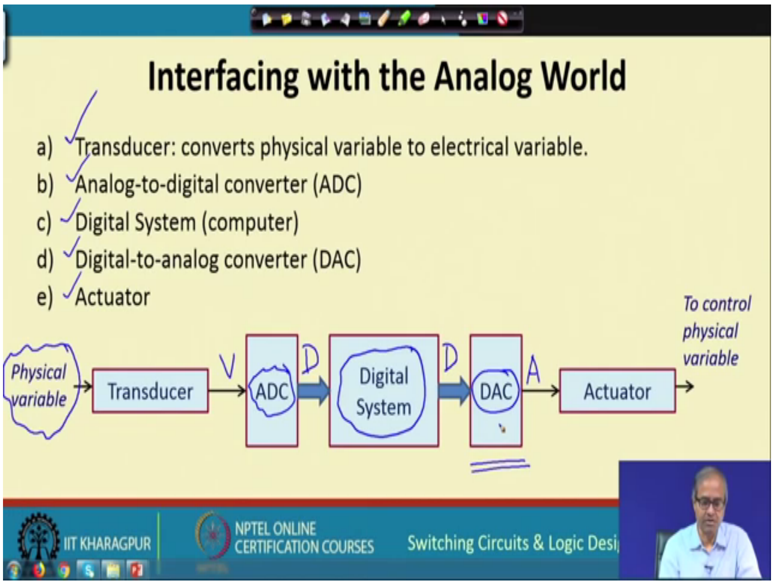

So, let us try to look into the overall picture as I have said. Let us see. Look at this schematic diagram. So, in this diagram, in the center we have our digital system where all calculations are processing are carried out. And in the environment input is coming from some physical variable. Now, as I have said the physical variable can be temperature, pressure, humidity anything. So, these physical variables are not digital in nature as I had said.

So, the first thing is that you have to use some kind of a sensor or a transducer to convert this physical variable into a voltage. So, you convert it into a voltage let us say V. Now, digital system cannot accept a voltage directly, it only understands 0 and 1 two discrete levels or digital levels. So, this continuous valued voltage that we have got that needs to converted, needs to be converted into an equivalent or proportional digital data. For that reason, we require a building block called an analog to digital converter which we shall be discussing later.

So, this ADC what it does it takes this voltage as input and generates a proportional digital data as output. Then this digital data comes to the digital system where whatever processing, you want to do can be carried out. And the result of the processing, which is again some kind of digital data let us call it D, it is fed to something called a digital to analog converter, the reverse of ADC. Digital to analog converter what it does, it takes this digital world and converts it into an equivalent analog voltage A. And there is an actuator which uses this analog voltage to control the physical variable of the environment.

Let us take an example suppose, we are trying to build a temperature controller means we want to set the temperature of an environment to some preset temperature, let us say 35 degrees. So, what do we do first, we sense the temperature transducer can be some kind of a some kind of a temperature sensor, there are so many kinds of temperature sensors available. You can use any kind of a temperature sensor that will convert the temperature into a voltage. Then the digital system will see that the equivalent digital data for that voltage whether it is below or above the preset value, that accordingly it will be generating an actuation signal, this actuator can be this actuator can be either a heater or it can be an air conditioning machine.

So, this actuator will be activating the heater or the air conditioning machine, so that the physical variable here temperature that you want to control is controlled in a proper way. So, in this overall picture, we require the transducers, which will convert the physical variable into some electrical signal. Then we have analog to digital converter, then in the digital system, which can be a computer or any kind of digital subsystem and digital to analog converter at the output side then the actuator. Now, in this lecture, we shall be first looking into some aspects of digital to analog converter.

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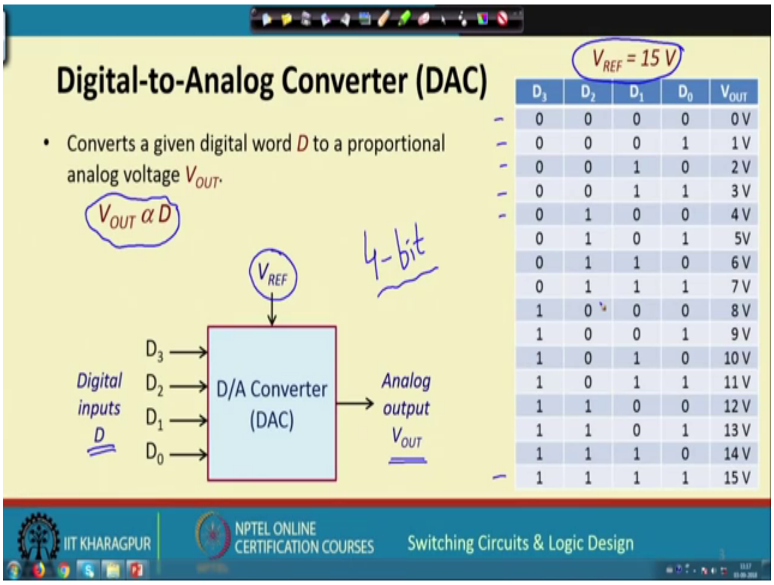

D_3	D_2	D_1	D_0	V_{OUT}
0	0	0	0	0 V
0	0	0	1	1 V
0	0	1	0	2 V
0	0	1	1	3 V
0	1	0	0	4 V
0	1	0	1	5V
0	1	1	0	6 V
0	1	1	1	7 V
1	0	0	0	8 V
1	0	0	1	9 V
1	0	1	0	10 V
1	0	1	1	11 V
1	1	0	0	12 V
1	1	0	1	13 V
1	1	1	0	14 V
1	1	1	1	15 V

Let us move on. So, what is a digital to analog converter? Let us try to understand this first. Broadly speaking, it is a building block which takes a digital data D as input and generates a voltage V out as output. This voltage is continuous in nature that is why you call it analog output. Now, the relationship between D and V out is V out should be proportional to D. So, whatever digital data we are applying the decimal equivalent of it, the output voltage should be proportional to that this is how a D A converter works.

Let us take an example of a 4 bit D A converter, we call it a 4 bit D A converter 4 bit, because it takes a 4-bit digital data as input D 0 to D 3. And there is a reference voltage which we typically apply to a D A converter the reference voltage determines what will be the maximum output voltage of the D A converter. Now, in the example that we are showing here let us assume that our reference voltage is 15 volts. And you see these are the different input combinations I am showing in decimal value 0 0 0 0 means, 0 0 0 0 and means 1, 2, 3, 4 up to 15. So, this D A converting work in such a way that depending on the input value V out will be 0 volts up to 15 volts. The output voltage will be proportional to the value of the digital input right. This is how a D A converter basically works.

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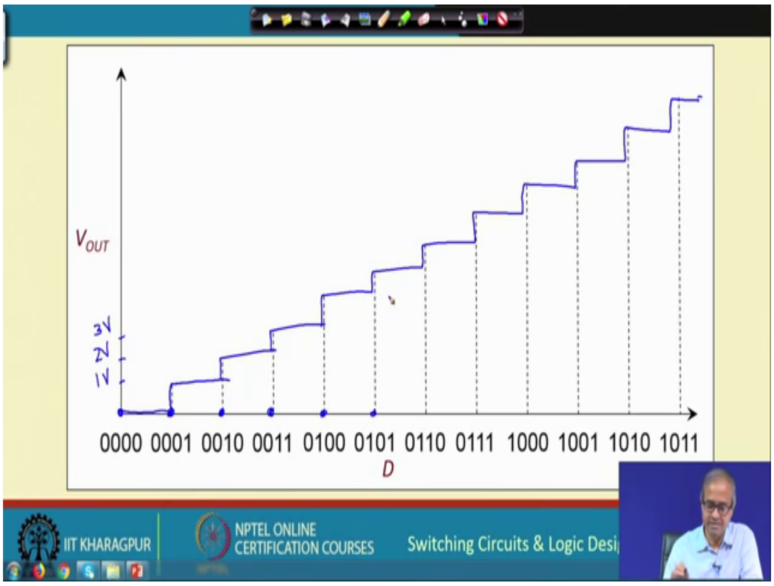

Let us move on. So, this figure shows the input-output relationship of a D A converter. You see here along the x-axis actually here I have taken the example of a 4 bit D A converter again. So, I am showing the four bit digital value 0 0 0 0 1, 2, 3, 4 I have shown up to 11, but it will continue till 15; and along the y-axis I am showing V out. You see in the input I cannot apply continuous data, I can either apply 0 or I can apply 1 or I can apply 2 or 3 that means, discrete values, because I can apply only discrete values.

So, in the output side also we can get only discrete voltages. For example, when the input is 0 I get a 0 voltage. So, when the input is 1 let us say this voltage is 1 volt; then when the input voltage is 2, this is 2 volts; then when the input voltage is 3, it is 3 volts like this. So, it will be a staircase kind of an waveform I get like this go goes on. So, depending on the input value I am applying as I increase the value of D, the output voltage jumps in steps, it does not increase continuously, because input I cannot increase continuously, I can only increase by discrete amounts. So, the output also increases in steps. This is how the characteristics of a D A converter looks like.

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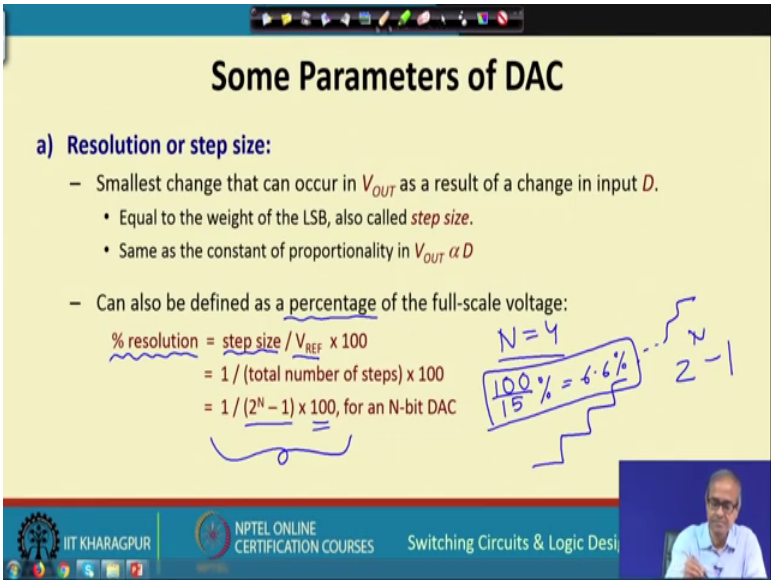

Now, we would talk about some of the parameters of this D A converter. So, when you design a D A converter, there are some parameters we talked about. The first important parameter is something called the resolution or step size. So, I talked about the output increases in steps. Now, what is the minimum width of that step? That is my resolution. You see suppose I specify the reference voltage as 15 volts. So, the maximum voltage can be 15, now if it is a 4 bit D A converter there can be 15 steps, 0 to 15; if it is a 5 bit D A converter, it will be 0 up to 32.

So, if it is a 4 bit converter, every step height will be 1 volt; for 5 bit it will be half volt 0.5 volt; for 6 bits, it will be one-fourth or 0.25 volts. So, as we increase the number of bits, the accuracy or the height of the step decreases that means, I can generate more accurate ranges of voltages in the output. This is what is defined as resolution or step size, defined as smallest change in the output voltage as a result of a change in D. See the minimum change in D will be equivalent to 1, 0 to 1, 1 to 2, 2 to 3, so you can say it is equivalent to the weight of the least significant bit. So, as if the least significant bit is changing that will be equivalent to a step of 1 right.

Now, typically we express resolution as a percentage, how? See step size I have already talked about. If you divide step size by the reference voltage, this multiplied by 100; this is defined as the percentage resolution. Step size see V ref is step size by V ref you can represent it like this 1 divided by total number of steps same thing and for an n bit D A converter number of steps will be starting from 0 there will be 2 to the power n minus 1 steps, so 1 divided by 2 to the power minus 1 multiplied by 100.

So, if you write it like this, then you will get the percentage resolution. Let us say for a 4 bit D A converter n equal to 4, the resolution will be 100 divide by 15, this much percentage. So, it will be how much 6.6 percent approximately right. So, the resolution will depend on the value of n. Let us move on.

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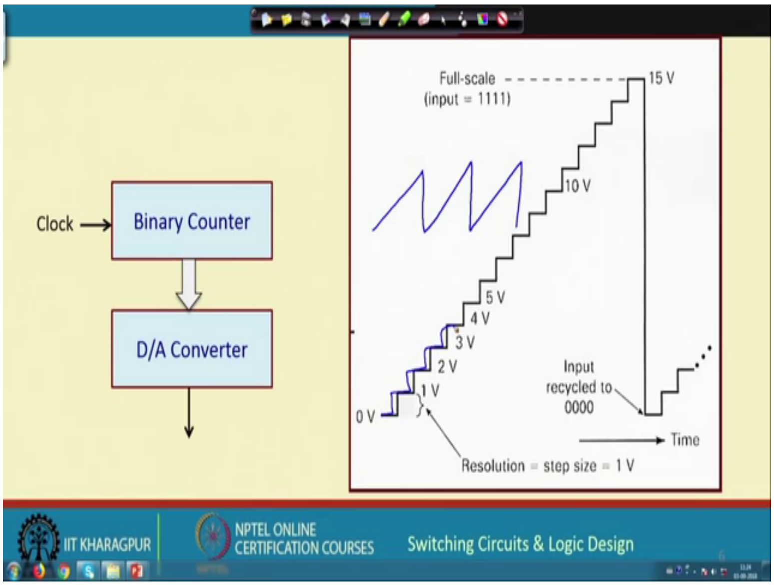

Now, suppose I connect a D A converter directly from the output of a binary counter and there is a clock. So, the binary counter is counting 0 1 2 3 4. So, the output of the D A converter if you observe on an oscilloscope you, will see that there will be a staircase kind of a structure generated, the output voltage will be increasing in steps. Suppose, it is a 4 bit counter, so it will be counting from 0 0 0 0 up to 1 1 1 1 and then again back to 0. So, this staircase will start from 0 here, it will go up to maximum 1 1 1 1; after that it will again go down to 0.

So, it will be a staircase kind of an waveform not like this it will be, like this it will be go up, then again down, again go up, again down, again go up, again down like this, but it is not a continuous thing it will be small steps right. This is how the output waveform will look like.

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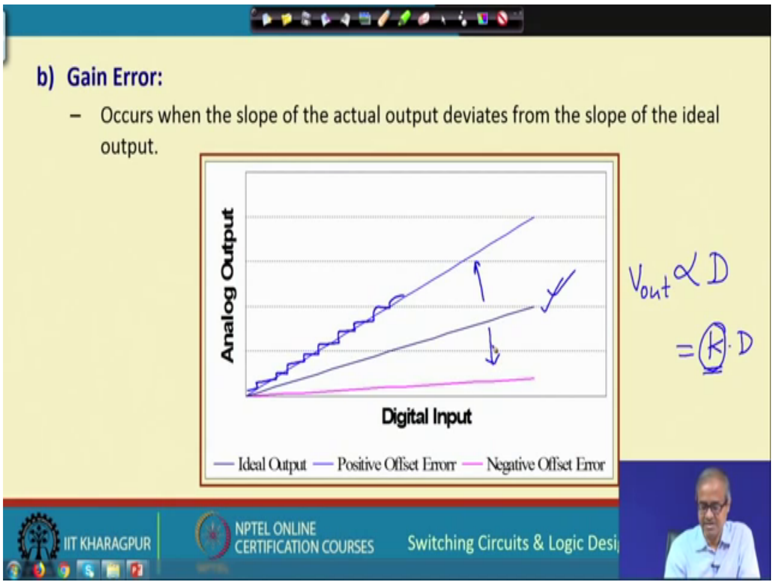

Now, there are some you can say errors in D A conversion process that can occur, first is gain error well we said that the output voltage V out is proportional to D, which means some constant of proportionality multiplied by D. Now, due to some design variations or some issues the value of K might change, if k changes well here I am showing as a straight line, but actually these are the steps, these are the steps I am showing it as a straight line approximately.

So, what will happen, the slope of this straight line will change, if the value of K changes. This is called gain error suppose this black one is the ideal output. So, if there is a positive offset error gain error, so you will be moving in this direction; if it is a negative error, you will be moving in this direction right slope will change.

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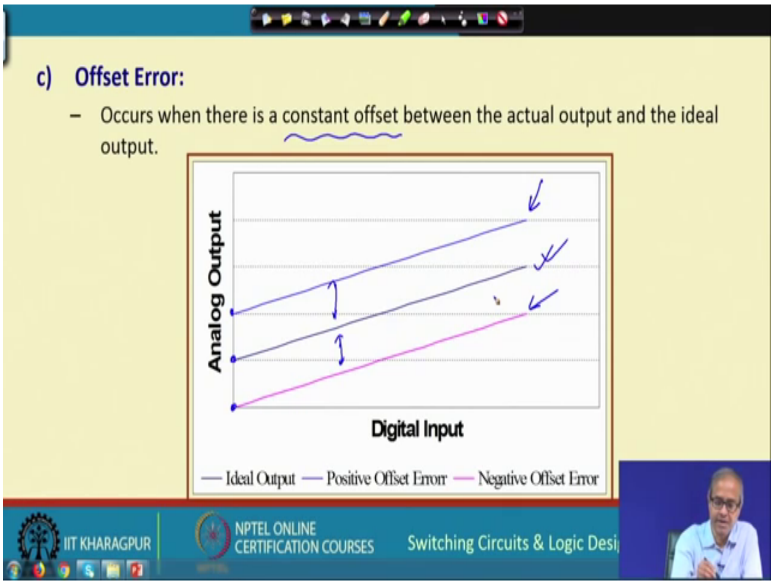

The other kind of error is offset error. Here the slope is not changing, but there is a D C shift, you say instead of starting from 0 maybe, it is starting from 1 volt sorry maybe it is starting from 1 volt instead of 0 volts, it is starting from 1 volt or let us say here. So, there will be a DC shift all along the curve and this separation is same; that means, the curves are still parallel, this is called offset error. There is a constant offset between the actual output and the ideal output. Suppose, say this middle one is the ideal output and this is the actual output or this is the actual output you are getting, there is a constant offset fine.

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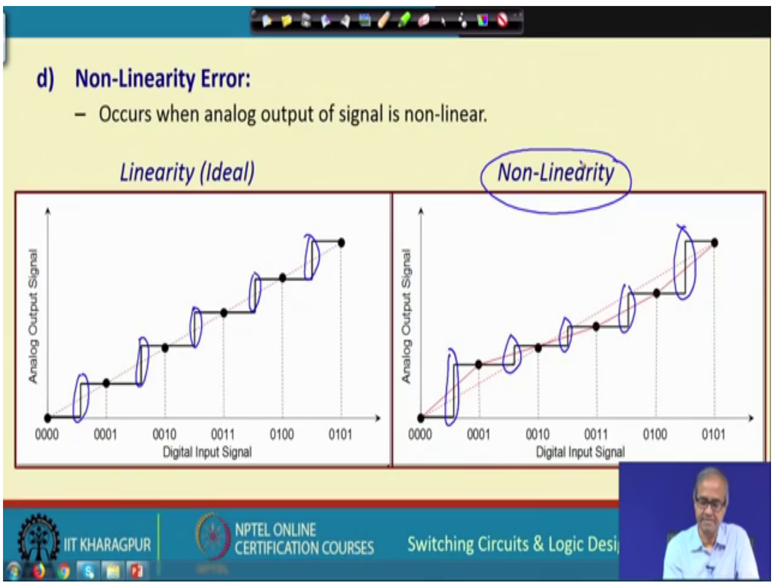

Then comes non-linearity; non-linearity means you see for a DA converter we said that the step height should be the same. So, this is the ideal scenario, so all step heights are exactly same, but you will see later that this D A converters can be designed using resistances. Now, if the value of some resistances change due to fabrication defect or because of some other error design error. So, what might happen these step heights may become different like it is shown on the right side, you see this step is larger this step is smaller, this is again smaller, this is larger this is even larger. This is called non-linearity, this is non-linearity error right.

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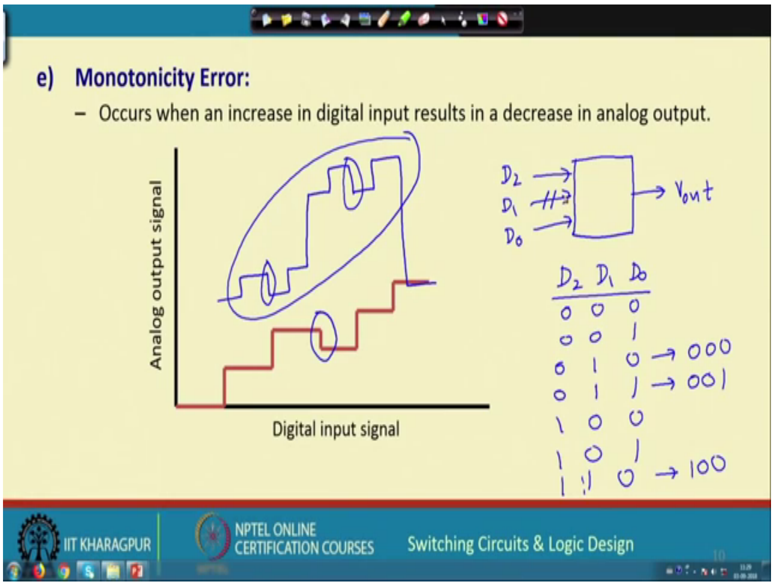

Then you can have another kind of an error which is called monotonicity error. Like normally as the digital input increases the output should be increasing in steps, but what you may see sometimes the output may decrease instead of increasing, but you may say that why it should happen, the input is increasing output should always increase it may happen due to some other problem. Let us take a very specific example. Let us consider a 3 bit D A converter, because it is a simple example you can work out, let us say D 2, D 1, D 0, and this is your V out.

Now, suppose while you are designing and making the connections, this D 0 connection you have forgot to make or there is a disconnection, this is disconnected. So, as you increase you see, if you just note down the values D 1, D D 2, D 1, D 0, it will start with 0 then 1, then 2, then 3, then 4 then 5 and so on, but because D 1 is not connected D 1 will be always 0. So, effectively this will be 0 0 0, this will be 0 0 1 this will. Then again, if you say 6 1 1 0, this will become 1 0 0. So, you see if you look at the output 0 1 0 1 4 5, so there will be 0 1 again 0 1, then there will be a jump 4 5, again 4 again 5 then back to 0. So, your wave form will be like. This you see there is a monotonicity error, sometimes it is decreasing. And it can happen, because of this some error in connection, somewhere might become open circuit right.

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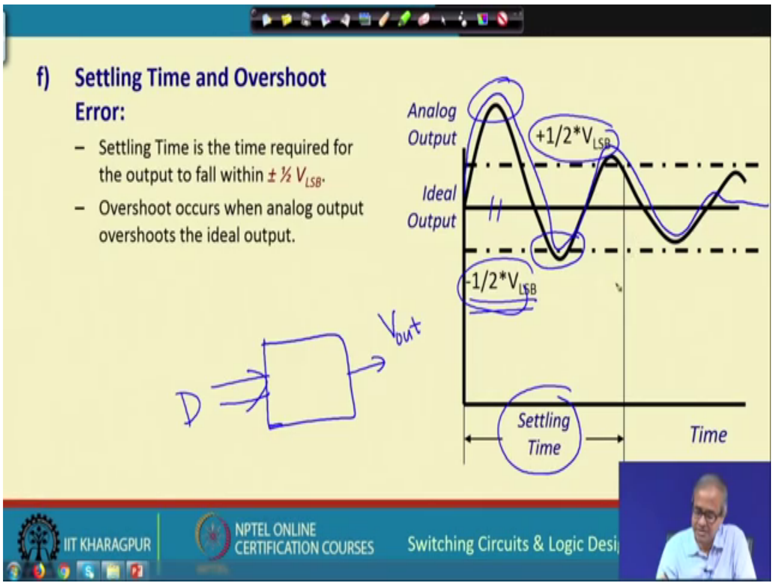

And the last kind of error let me talk about is settling time and overshoot error. Settling time says see, when you have a D A converter, you are applying a digital input D and you are getting an analog output V out. So, as soon as you give the value of D output is not obtained instantaneously, there can be a delay before which the output stables. This is called settling time and during settling time there came an overshoot. Suppose this is the ideal output level, this one. Sometimes the output can go up go down again go up and go down before settling down this is called overshoot or this time this part will become undershoot.

And setting time is after how much time means even due to this overshoot or undershoot, the output will fall within plus minus half of the step size of the or the LSB equivalent voltage plus half to minus half. So, in this example, settling time is up to here right. So, these are the different kind of errors that I talked about that may occur in a digital to analog converter.

So, with this we come to the end of this introductory lecture. From the next lecture onwards, we shall be talking about how to design first digital to analog converters then we shall talk about analog to digital converters.

Thank you.