Digital Circuits
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Lecture – 38
Data Converters
(Contd.)

So, the speed is another factor that determines the selection of this DAC. So, rate of conversion of a single digital input to its analog equivalent, so, that is called the rate of conversion, that is, you give a particular input pattern, so, after how much time the analog signal comes to the proper value. So, that gives the rate of conversion for the digital input.

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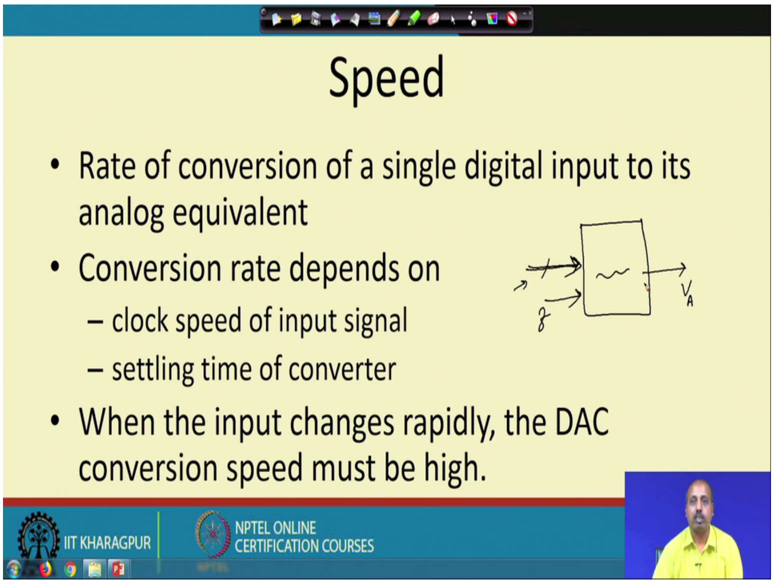

Then conversion rate it will depend on the clock speed of the input signal. So, because if the input signal is changing at a particular rate, then the conversion must be done before that next change occurs. So, if we have got this DAC if we have got this DAC operating this input is coming at some rate then this it is coming at some frequency f, then the conversion must be faster than that frequency otherwise it is not acceptable. So, depending upon the rate at which the processor is doing the computation so, we have to convert at that rate. So, clock speed of the input signal becomes an important point.

Second point is the settling time of the converter that is after you have given a particular pattern. So, it does not if the final analog value voltage is say V A then it takes some time for the analog output to get settle to V A. So, sometimes it goes into an as a damped oscillation oscillatory behavior. So, as a result it takes some time to settle to V A.

So, this clock speed of the of the input this settling time of the converter so, that is this is another issue that is after you have finished applying this pattern how much time it takes to settle to the value. So, before that this input should not change, ok, otherwise this behavior will be unpredictable. So, that is why this conversion rate will also depend on the settling time of the converter.

And, when the input changes rapidly, so, DAC conversion speed must be high. So, this is particularly true when we have some high end microprocessor or microcontroller which can produce output at a very high rate. So, then this DAC that we take so, that should also be able to cater to that particular speed. So, that is why this choice of DAC is application dependent and we have to be careful there.

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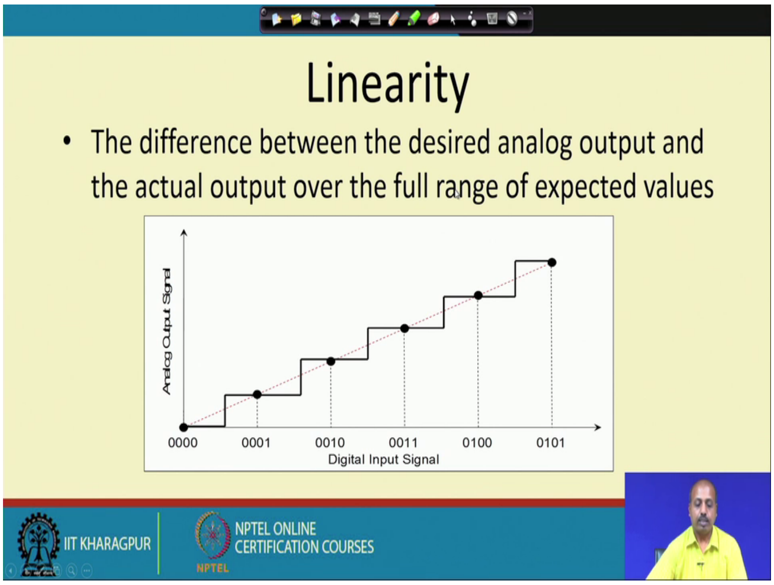

The next important issue that we have is the linearity. So, difference between the desired analog output and the actual output over the full range of expected values. So, you see that if this is say the digital input signal is like this. So, 0000, 0001, 0010 then the corresponding analog output values that we expect is at this point we expect the analog value to be this, then the next one are you expected values. So, this is the ideal behavior that we have. So, this is the, this should get so, here the step size is more the step size is same the analog voltage is not increasing rapidly. So, it is following a linear pattern. But, since this is ultimately some circuit so, these resistances and this op amp so, it will have it is own properties, as a result you may not get this linear behavior always. But, however, we want this linear behavior.

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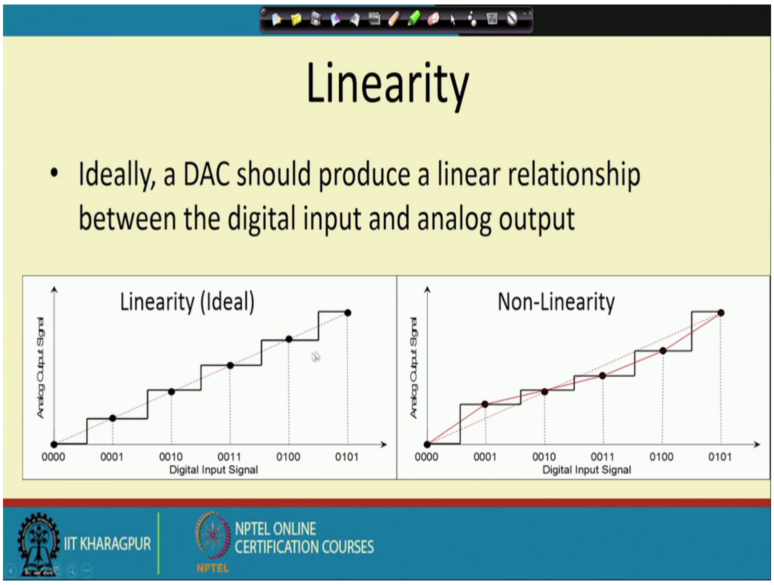

So, ideally so, this is the, this is what I was talking about. So, this is the linear behavior, this is the expected behavior on the other hand. So, we can get a non-linearity. So, it may so happen that when you change from 0000 to 0001 the voltage analog voltage increases from this value to this value, ok. So, it becomes high like this. Then when you change from 0001 to 0010 the output does not change that much. So, it increases only by this small amount of step.

Similarly, here from 0010 to 0011 it increases by this much; whereas, at later point it increases at a different rate. So, ideally we want that this step size should be same, but as I said that depending upon the circuit parameters. So, you may not get this a straight line this as say equal step size behavior so, you can there may be problem so, you can get irregular sizes and this analog output may become irregular. So, the linearity the linear relationship between digital input and analog output may not be maintained.

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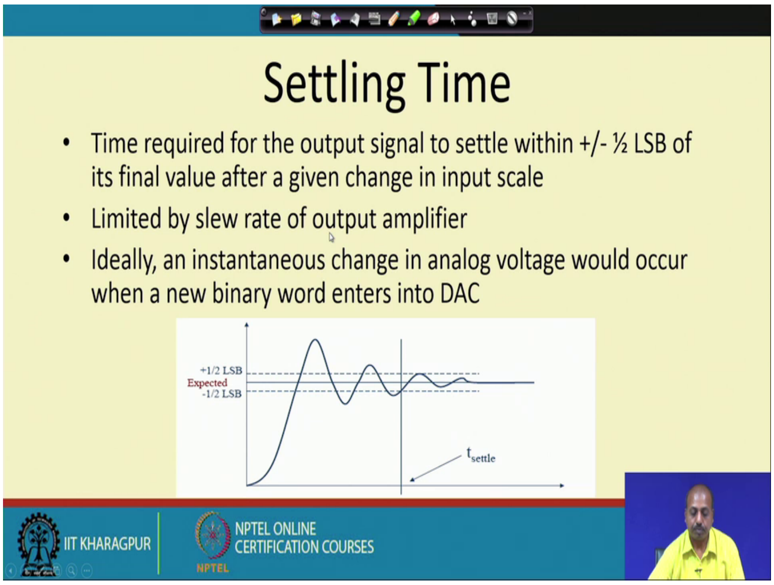

Next issue that we have is the settling time. As I was telling that so, we have got say the some analog or some digital value change as a result so, this is the expected output. So, this straight blue line so, this is the expected output. However, the analog value it does not settle to this one immediately. So, it increases like this overshoot this point then it again comes down undershoots, then it goes like this. So, after some after some time it settles to the value.

So, if this is the amount of change that is the Vref divided by this LSB voltage change. So, this is the plus due to this plus half LSB and minus half LSB change so, whatever be the difference in these 2 voltages. So, from your digital circuit there from your DAC circuit that we have so, we can compute what will be the analog voltage change. So, if we go from minus half LSB to plus half LSB; that means, 1 LSB change.

So, if you take that region as the region of compromise then we can say that when the output becomes within confined within that range so, we are happy. So, then it will be then it settles down. So, so, this time is that t settling time. So, starting from the change in the digital input to this settling time so, this is known as t settle. So, this is the time required for the output signal to settle within plus minus half LSB of its final value after a givens change in the inputs input scalar there, there is the input digital value. So, that is that that is the settling time for the DAC.

It is limited by the slew rate of the output amplifier. So, amplifier it will have some sleeve rate and if you look into the operational amplifier literature. So, you can find the this thing. So, this is the, this is actually gives us that timely how fast it settles to the proper value. Ideally, an instantaneous change in the analog voltage would occur when a new binary word enters into DAC. This is the ideal behavior that is the DAC becomes produces the output immediately, but it will not happen.

So, it will have this t settle. So, as I was telling that if your processor is giving digital output which are faster than this t settle then naturally the DAC will not be able to convert all the digital values to their proper analog ones. So, that way there will be problem. So, while choosing the DAC to be used so, we have to be careful and we have to select this t settle we have to select that DAC properly. So, that the rate at rate of data change for the application is can be accommodated within this t settle time.

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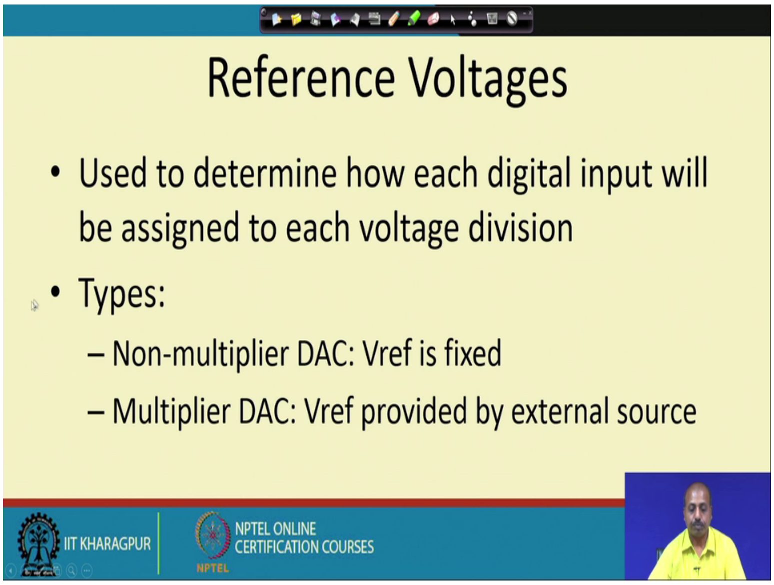

Next important issue is the reference voltages. So, it is used to determine how much each digital input will be assigned to each voltage division. So, we have so, this is basically. So, as I said that the voltage the, this with a change in the bit pattern. So, number of levels that we have is the Vref divided by 2 to the power n. So, this n will determine one value. So, this individual steps ideas again Vref divided by 2 to the power n.

So, if your Vref is high enough then this accordingly you will get significant change with the step in the step size, ok. So, with us we each individual with each change in the digital count value so, you get a significant change in the output; whereas, if Vref itself is low then this change is not that much significant so, that may not be able to activate the actuator that we have at the output of the DAC. So, that may becomes a problem.

So, it is used to determine how much digital input will be assigned to each voltage division. So, there are two types of this reference voltages; one is non multiplier DAC where behave Vref is fixed and this multiplier DAC where the Vref will be provided by some external source. So, some of the DAC chips you will find that this Vref value is fixed by the designer, some of the some of the DAC is that we have some DAC chips you will find that there is a Vref pin that is available and there is a range that is specified. So, you can apply some Vref in that range and as a result it will convert the voltage value according.

So, many times what happens is that you need both an positive and negative voltages for the for the analog output, so, in that case your Vref can be both positive and negative. On the other hand if you want if you are looking for only positive output then this Vref can be set accordingly. So, many chips they have got this type of configurations.

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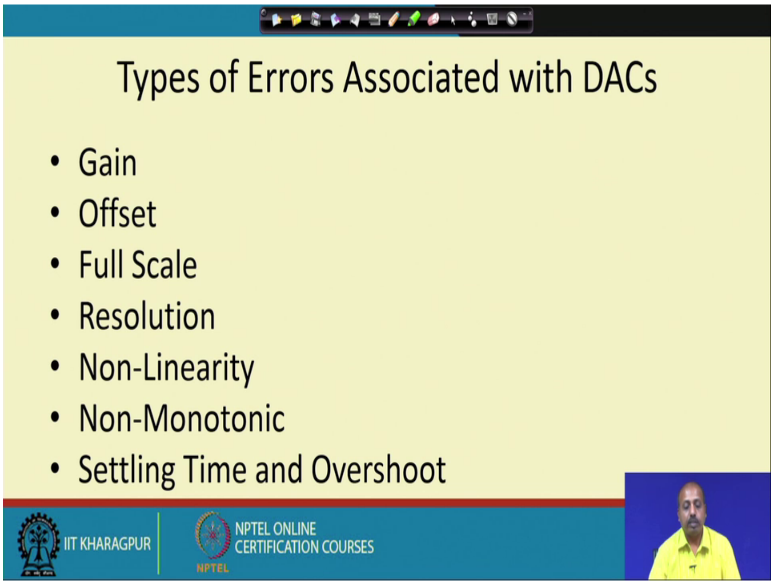

So, the types of errors that we have with DAC is the gain part, offset part, then the full scale full scale range that you get, resolution, non-linearity, non-monotonicity and settling time and over short overshoot. So, these are the different types of errors that we can have.

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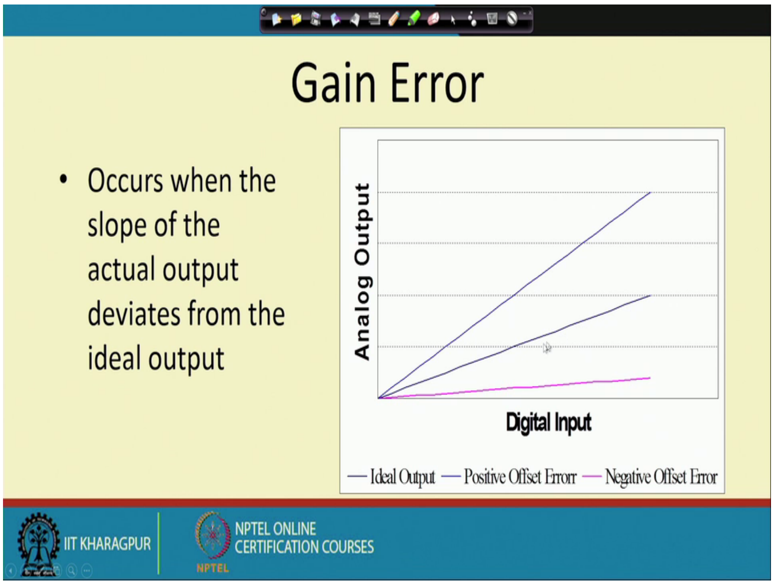

Gain error: so, it is like this. So, this is my ideal output, ok, so, depending upon my DAC design so, I expect the output to be like this then, but it in reality it may so happen that you have you get the output like this pink line or this blue line. So, this is the positive offset error and this is the negative offset error. So, this occurs when the slope of the actual output deviates from the ideal output. So, both of them are straight lines this blue line as well as this purple line both are both are linear both are going in straight lines, but they are deviating from the at the actual output the ideal output. So, this is known as the gain error. So, we naturally we would expect that the gain error to be less.

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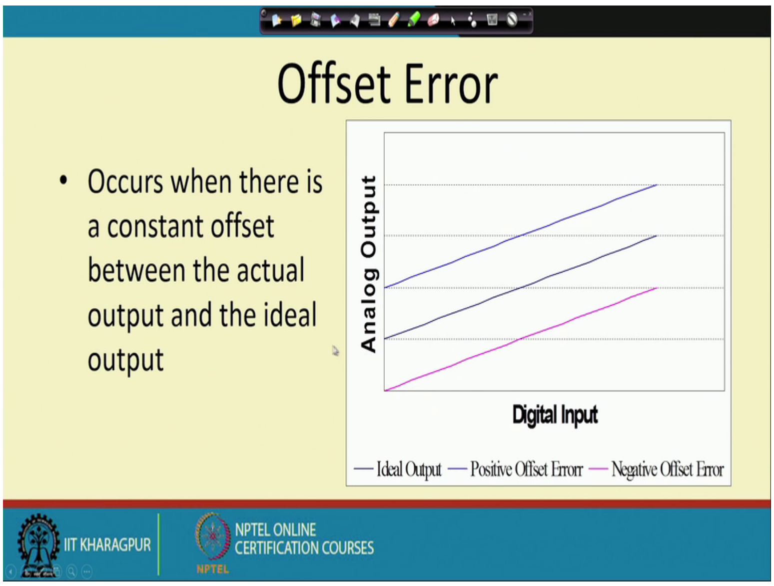

Then, there is an offset error so, offset error says that, it occurs when there is a constant offset between the actual output and the ideal output. So, this is the ideal output and always there is an offset, ok. So, this offset is fixed whereas, for gain error, so, gain is not fixed, but this offset error so, there is this difference is fixed, ok.

So, so, it may be possible that offset error we may add some constant value and get that or some positive or negative value and that way that offset gets nullified. So, this occurs when there is a constant offset between the actual output and the ideal output. So, that is the offset error for the DAC. Again, we will like that it should be reduced.

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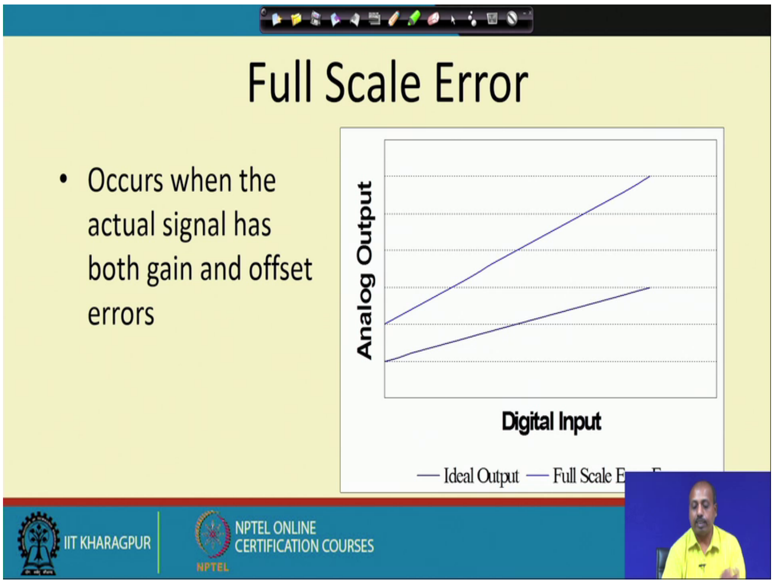

And full scale error, so, this when the output has got both gain and offset errors so, then that is the full scale error. So, if there is only a gain error then this it will be following the similar pattern like this, but here you see that the gain is also changing and offset is also changing. So, none of them are fixed. So, as a result so, you get this gain and offset error. So, this is known as full scale error. So, this is the ideal output and this is the full scale error output. So, that way we can think about we definitely we like to have DAC where this full scale error is minimum, ok.

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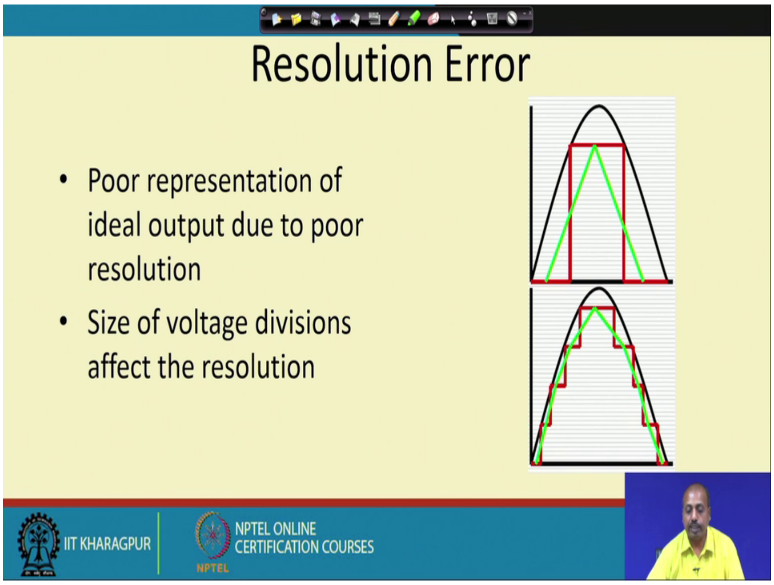

Then there is resolution error. So, resolution error is like this; suppose, we have to realize this sinusoidal wave. So, we want to output this sinusoidal wave and that DAC that we have. So, DAC it has got only the voltage levels that we have is this is one level and this is another level only these two levels are available. So, to approximate the sine wave this part so, what the DAC does is that the it first outputs this, the digital pattern that we feed so, it first output this voltage and then it output this voltage.

Now, if we average over time the behavior becomes more of a triangular type. So, if you just a put a put it put the output on some oscilloscope so, you will find something like say a triangular type of behavior because so, if you average it over the period, ok, so, then you if you integrate over this period, so you will be getting a triangular type of behavior.

Now, instead of having only these two levels, so if we have got more number of levels like here in this case we have got 1 2 3 4 5 levels. So, if the DAC is made to produce all the voltages at these 5 levels then you get a better approximation of the sinusoidal wave. So, this is the resolution error. So, I we say that in the second case the resolution is more because I for the same within the same maximum voltage I have got more number of digital or the analog voltage levels that can be produced by the DAC.

So, it is a poor representation of the ideal output due to poor resolution. So, this is the resolution error. So, resolution is poor. So, resolution expression is given by Vref divided by 2 to the power n, as we know. Now, if we have do not have many levels available so, if the resolution value is low then naturally we it may be the case that we do not have so many voltage levels available. So, it will give a poor resolution. The size of voltage divisions this will affect the resolution ok. So, that we have already explained.

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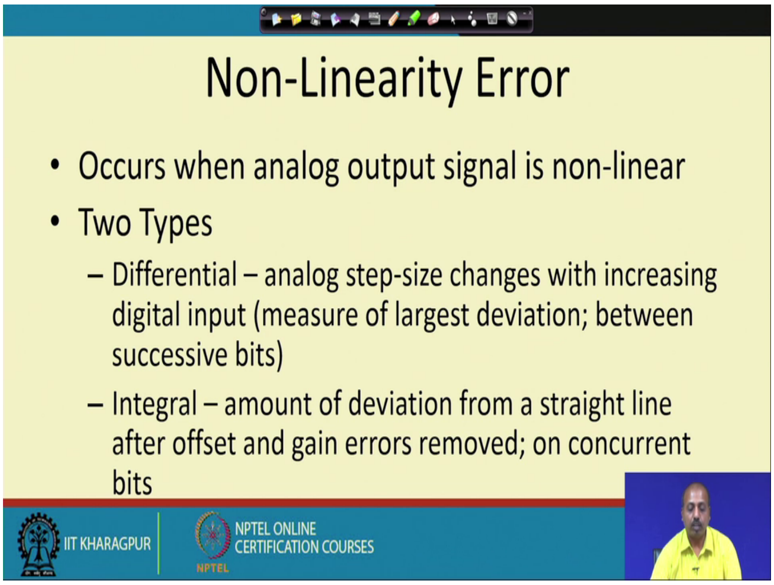

Then there is a non-linearity error. So, occurs when the analog output signal is non-linear. So, this is so, as I said that the analog output that you get we may not be following a linear relationship. So, there were two types of non-linear behavior; one is the differential for the analog step size changes with increasing digital input that is if you between successive deviation so, between successive bits so, you can measure the measure may measure of largest deviation. So, that is the differential nonlinearity error.

And, the integral errors the amount of deviation from the straight line after offset and gain errors removed so on subsequent bits. So, if we see this so, thus this is the differential type of integral type of non-linearity error. So, both of them can be measured; one is the differential type, that is if you change if you change from one position to another position so, what is the maximum amount of change; ok. So, measure of largest deviation between successive bits so, that is the differential change and the integral changes, so, if you so from the so, if you so, if you take this offset and gain errors so, if you remove this offset and gain error so you will get the ideal behavior, then from that how what is the deviation on concurrent bits.

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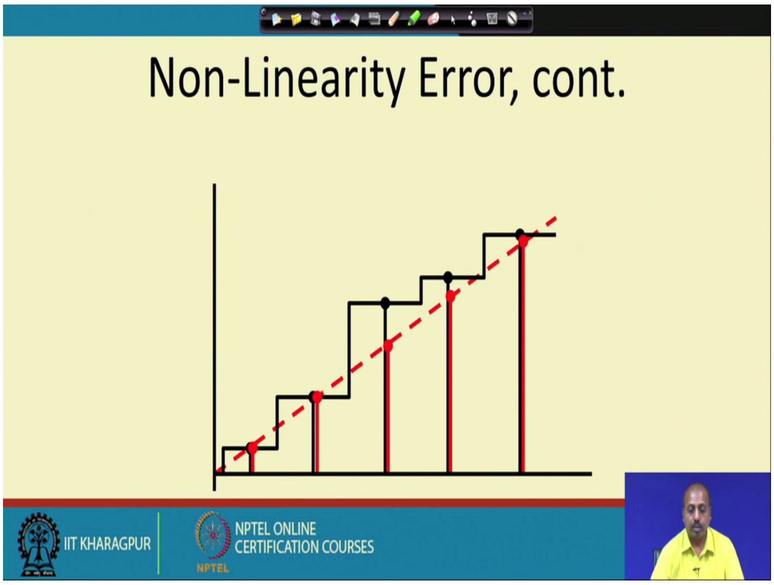

So, this is the nonlinearity error as I was telling that this is the ideal behavior that if you put this digital value. So, you get this you should get this analog signal. So, this is the ideal behavior, but due to this non-linearity this step size is different. So, you get the behavior like this, so, it produces different amounts of error. Whereas; the ideal behavior should have been this red dotted line, so, what you get is this black line. So, that is a nonlinearity error.

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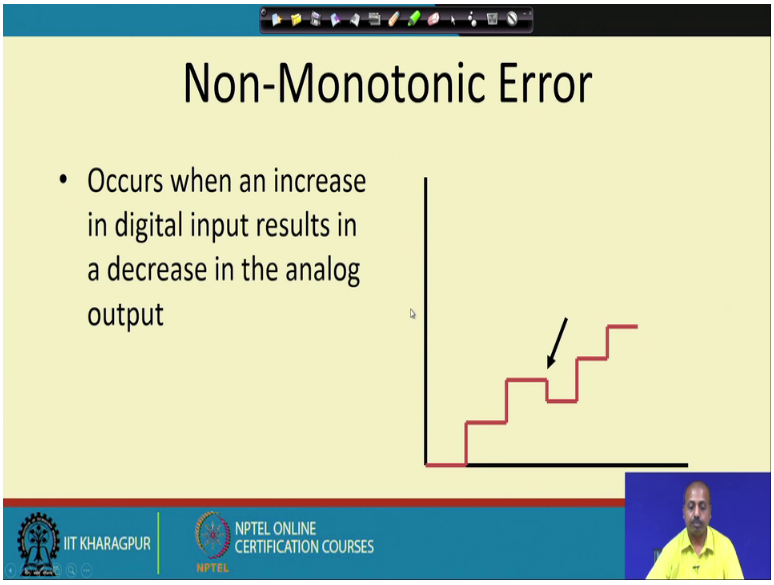

Then there is a non monotonic error. So, monotonicity means as it is increasing or decreasing in a particular sequence in a so, as you are increasing the digital input. So, it is expected that the analog output is also increased and if you decrease the digital input the analog output should decrease. So, we are not bothered about linearity here. So, we are suppose we accept that this linearity is not a concern, so, we just want that with increasing digital value the output should increase and decreasing digital value output should decrease.

But, it may so happen where that for some bit patterns some so for some digital inputs output instead of increasing it decreases. Like here; so, when you put this digital value, so it produces this voltage then you then you put this digital value so, it is the analog corresponding analog value. So, like this now after this when this digital value was given the output was like this, after that when we give these digital values output reduces like this. So, though the second digital value that we have given is higher than the previous digital value, but the analog value has reduced.

So, occurred, so, in an increase in digital input results in decrease in the analog output; so, this non-monotonicity error occurs; so, naturally this is not the, this is not desirable. So, my DAC should not have this type of behavior, but sometimes if we know that it has got a non-monetary non-monotonicity at some points of values. Then we can avoid those values by the processor toward the processor may avoid those values to be outputted to the DAC or some other care may be taken, but this ideally this should be avoided.

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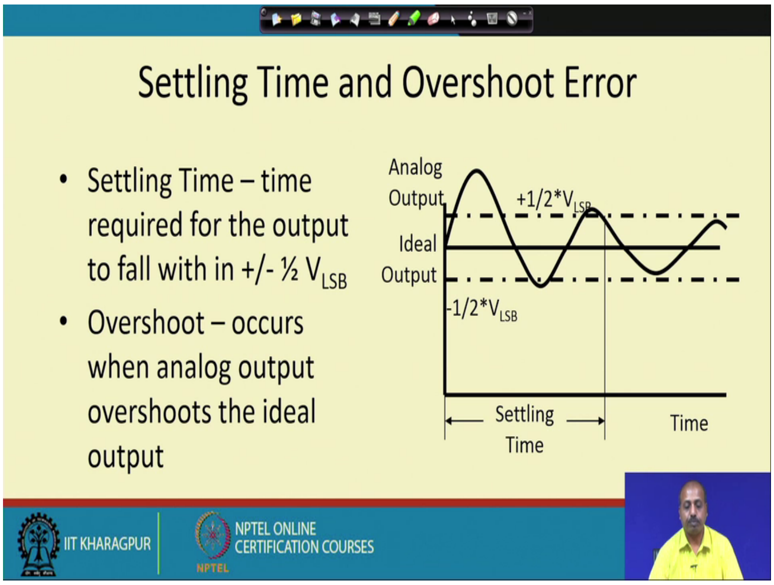

Then settling time and overshoot error. So, we have already explained to some extent so, let us just revisit it. So, this is time required for output to fall within the plus minus half into V LSB. So, this is the as I said that ideally this is this is the behavior. So, it should come to this value, but the analog output becomes like this. So, it shoots up like this and then it comes down so, it goes like this so, from this after this point so, you have got this output contained within the plus minus half V LSB voltage. So, as a result we say. So, we say that when it comes within this range so, that is the settling time.

So, the time needed from the change in the digital input to the change to the point till this analog output comes with the plus minus half V LSB. So, that is the settling time for the DAC. And overshoot, it occurs in the analog signal analog output overshoots the ideal output. So, this is the overshoot. So, whether it is desirable or not, that is a question. So, sometimes if we if the circuit is too sensitive then we may not like this overshoot to be there, but it cannot change instantaneously. So, normally we get a behavior like this only.

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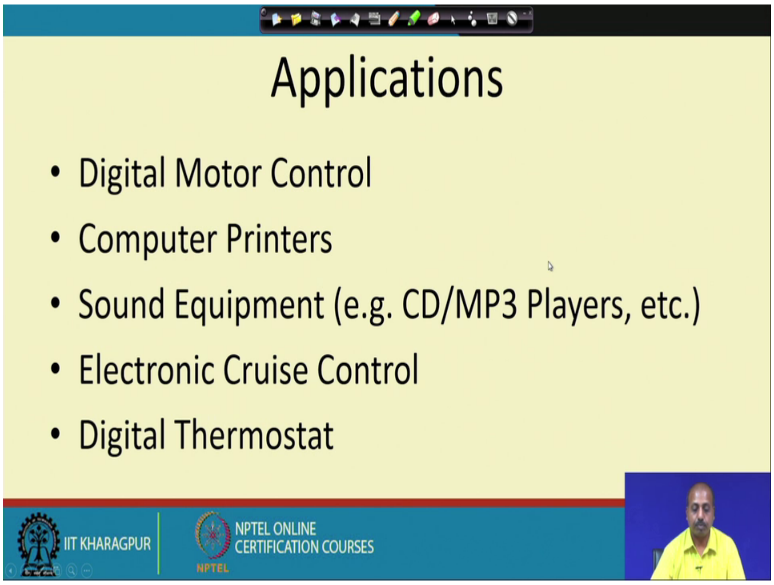

So, where are we going to apply these DACs? One possible application of DAC is the digital motor control. So, digital motor control; so, motor would require some analog voltage so, as you increase the voltage then its speed of operation increases. So, as you reverse the polarity of the voltage then at the motor rotates in the reverse direction like that. So, from a digital signal so, if you are going to control the motor so, then you need a DAC, so that this digital value is converted to analog and then it is applied to the motor. Computer printers so, printers you have to activate some of the keys and then accordingly the key should go up and it should get printed depending upon the printing technology that we have. So, there also we have got applications of this DAC.

Sound equipment like these audio players basically. So, the volume or the pitch or so, that the signal that is controlled by the processor and then when it is given to the player so, before that this digital value has to be converted into analog. So, most of the songs and media data that we have a digital in nature; so, when you are trying to put it onto a player. So, we have to convert it into analog values

Then cruise control like you so, you have to control some vehicle or a missile in some direction. So, there also we have we go for digital control because of this error tolerance and all, but then how to control that cruise, so, that becomes and that the. So, for that we need this digital to analog converter and digital thermostat so, basically these temperature control mechanism. So, there also you need this digital to analog converter for doing controlling the thermostat.

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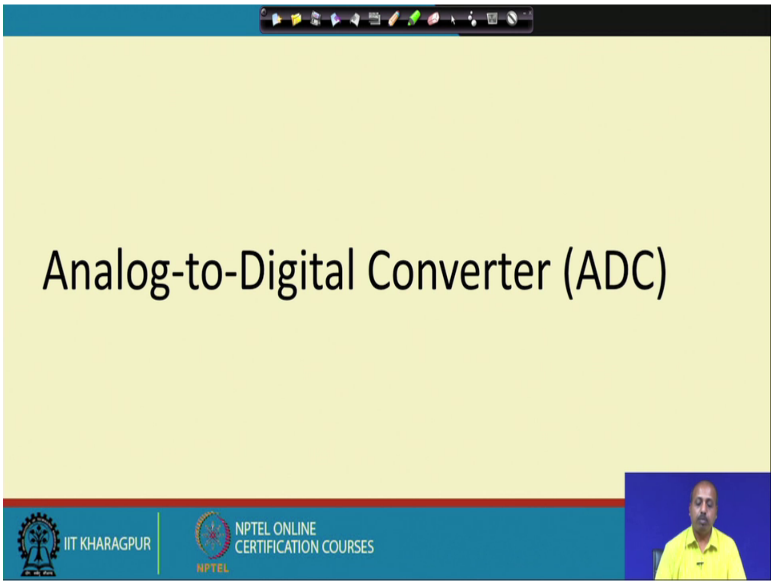

Next we will be looking into another module which is known as analog-to-digital converter or ADC. So, this is the other way. So, digital to analog converter, so, it was converting a digital signal to analog signal. This analog to digital converter it will convert an analog signal to a digital signal and once it is from the environment the signals that are coming there analog in nature and then we are converting them into digital value and then the this digital value is being fed to the processor for processing.

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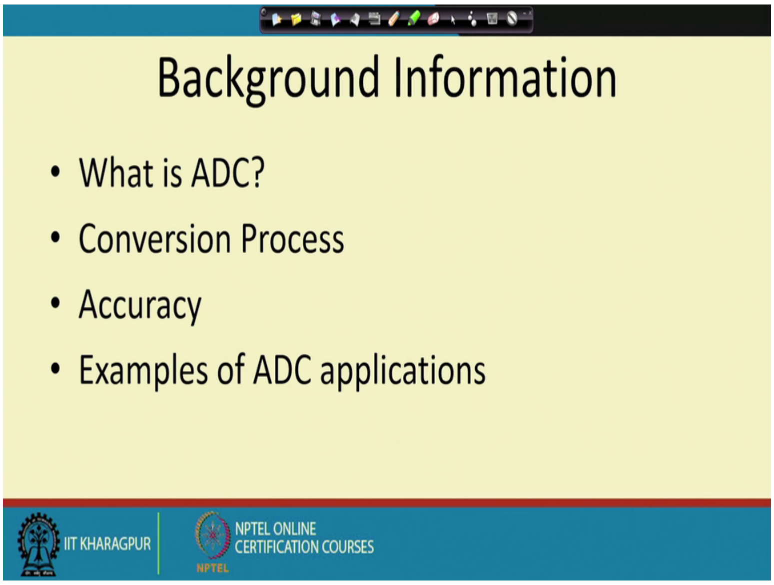

So, we will be discussing about this point like what is ADC? What is the conversion process? What is the accuracy of the f and ADC and some examples of ADC application. So, we will go in this sequence.

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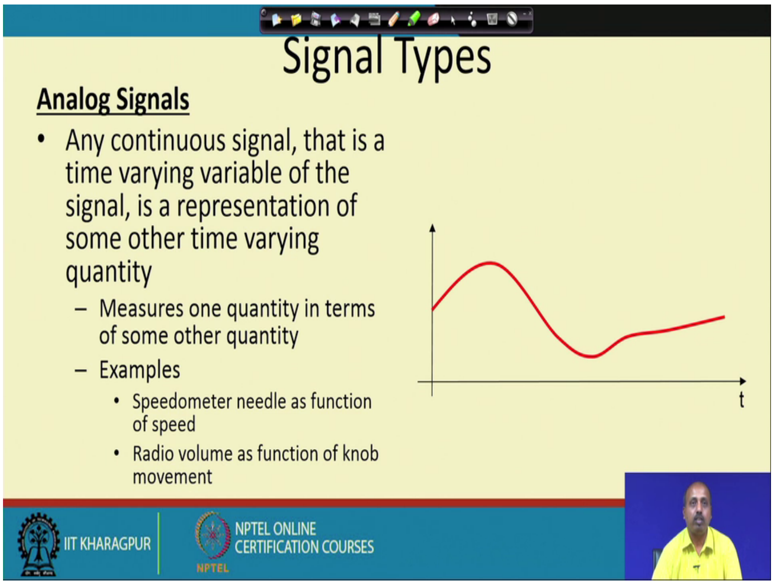

So, just go back so, if we go back into the types of signals so, at the beginning of our course so we have seen that there are general there are one type of signal which is which is the coming from the nature so, it is the analog signal. So, most of the signals that you get are analog in nature for our ease of processing we convert them into digital, but the actual signal that we get from the environment or the actual signal that we need to produce to the environment for controlling it some equipment or something. So, that is going to be an analog signal.

So, any continuous signal that is that can be represented by a time varying variable so, is a is an analog signal and it is representation of some other time varying quantity. So, the time is varying, so, the time is one parameter and this time varying quantity is what we want to represent. So, for example, if we are representing the distance covered by a train so, with the passage of time so, we can we can see you can find out what is the distance covered and then the, if the distance that is covered is coming is sensed by some sensor and then it is coming to us. So, that way it is going to be some voltage value that is there.

So, basically or say the temperature monitoring system so, with the passage of time temperature is varying, now the temperature is the time varying variable that we have. Now, the temperature value so, it by means of temperature sensors so, they are converted into electrical signal and as a result that electrical signal becomes a time varying signal and that represents the original time varying signal which is the temperature. So, that is why the definition is like this that it represents a time varying signal in terms of another time varying electrical signal.

So, measures one quantity in terms of some other quantity. So, for example, speedometer needle as function of speed. So, speedometer needle so, it represents the speed of the vehicle. So, this is the needle is moving so, that is a physical thing that we have physical signal and then this actual physical signal that is changing is the speed of the vehicle. So, that way one signal is representing the, another time varying variable.

Then radio volume as function of knob movement. So, if we say there is a volume knob of some device and if we just rotate that volume knob, then the volume is either increasing or decreasing depending upon the turning. So, the turning is the actual mechanical variable that is changing and then that is going to affect the volume. So, volume is becoming the signal that we see from the electronic side.

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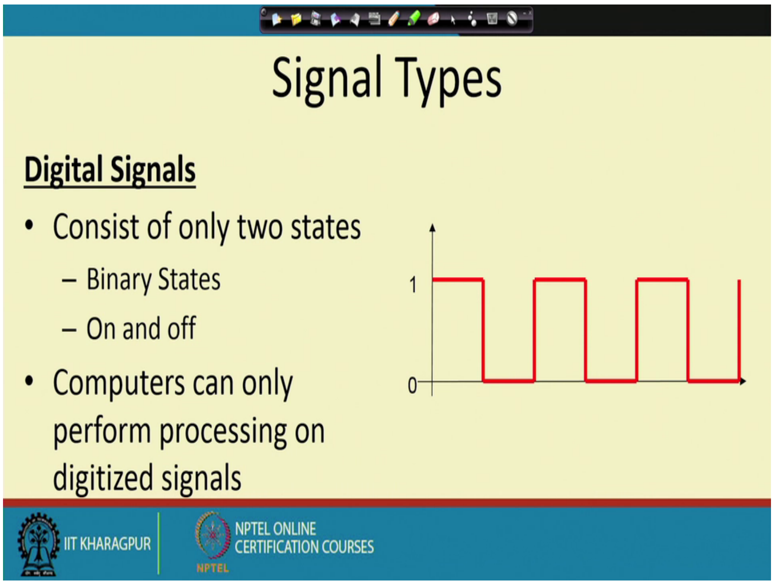

Another type of signal that we know is the digital signal that consists of only two states binary states or on-off states. So, they so the so the either 0 either low or high often represented as 0 or 1 or on or on and off like that. So, computers can only perform processing on digitized signals. So, that is the problem. So, we have got this the digital signals only in the computer system.

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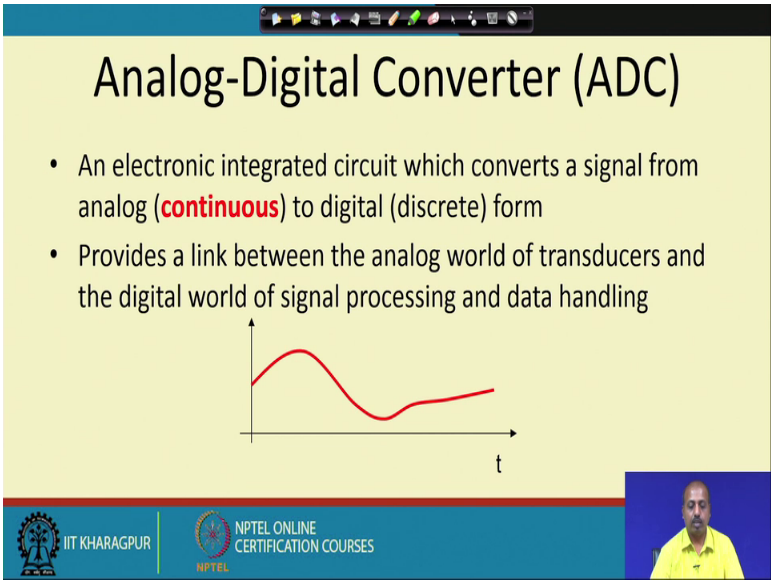

So, this analog to digital conversion; so, this is an electronic integrated circuit which converts a signal from analog to digital form. So, analog is continuous and digital is a discrete form and it provides a link between the analog world of transducers and the digital world of signal processing and data handling. So, transducers so, they are actually devices which can sense some physical quantity and convert it into electrical signal. So, that is the transducer and once we have that once we have some physical data converted into electrical signal. So, that physical data may be say temperature, may be pressure, may be some gas or whatever. So, there can be different types of physical quantity that we would like to that we like to measure and that is converted into some electrical signal by means of the transducers.

And, then they are converted once if they are converted into digital signal. So, they are now plug handled as by this is the computers or other digital signal processing equipments and the data is handled accordingly in the digital form.

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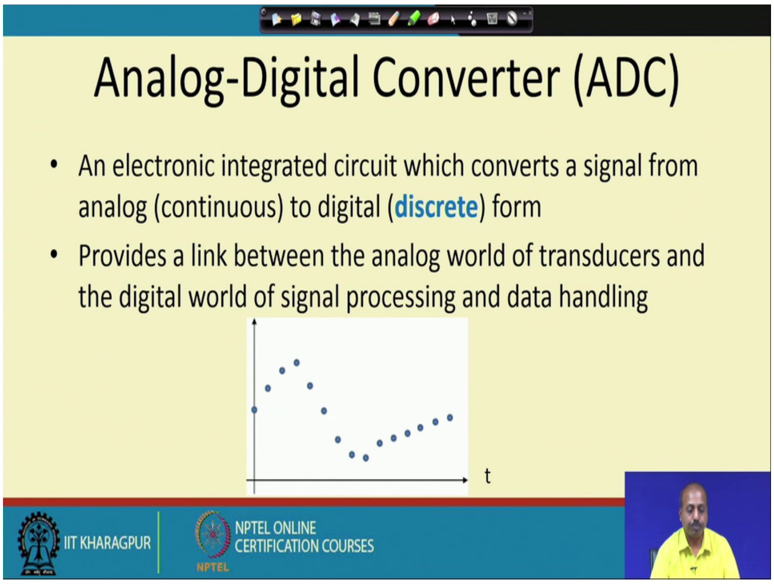

So, an electronic integrated so, this ADC is this ADC is an electronic integrated circuit which converts the signal from analog to digital form and it provides so, this is basically the signal that we have. So, maybe we just look into this signal at some discrete points of time and we see that it be its values are like this. So, this is basically a sampling of the signal at different time instants.

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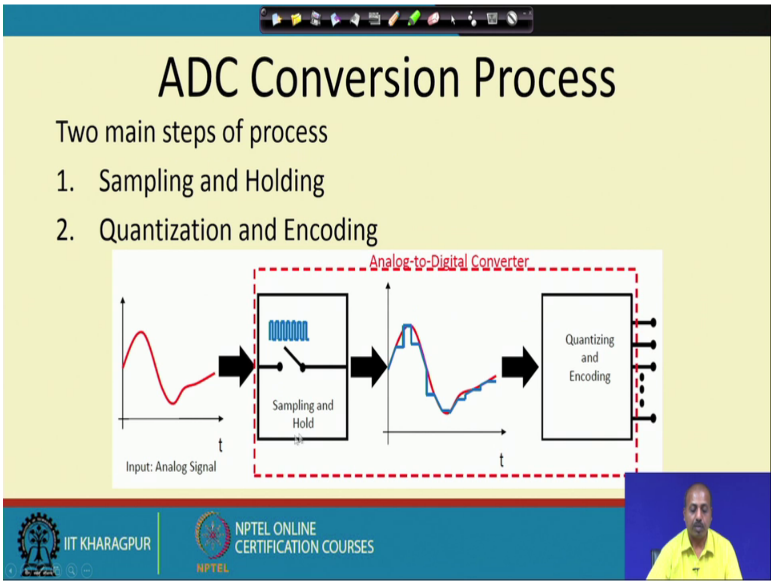

So, the ADC conversion process so, it has got two main steps, one is called the sampling and hold sampling and holding and the second part is the quantization and encoding. So, what is happening so, this is the actual analog signal. So, there is a sampling and hold circuitry which will sample this signals at some intervals of time. So, this so, though the analog signal is continuous, but to convert into digital signal so, we need some value at some fixed point of time. So, that value can be converted.

So, I cannot design a circuit that can go on converting these analog values continually. So, instantaneously it cannot convert into the value, because the circuit will have it is own delay. So, if the input is not stable for that much period of time. So, I cannot convert it into any other form. So, the so, digital any digital circuit I it will require the input to be constant for some amount of time.

For so to ensure that the input is constant for some period of time so, the input is sampled at some periodic intervals of time; so, you can think of this sampling as a switching as a switch and which has got this is. So, this sampling is done when the switch signal value is high, the switch is closed you can say, when the switch is closed then the, this value comes here and when this switch is open that is a low then here you do not get the output. So, the previous whatever value was there so, that continues to be available here.

So, that is if this is the redline is the analog signal, then depending upon the pulse that we are getting so, maybe if during this time period signal the switch is closed, as a result you get this part of the output, but from this point onwards the sampling switch is open. So, you do not get any further value. Again, at this point the sampling volt switch is closed. So, again you get this part of the red signal again it is closed on this point. So, you do not get this red part again you get it from this portion.

So, that way whenever the switching gate is closed so, you get the analog signal fragment available at the at this output point and whenever it is closed whenever it is open so, it does not get the thing. So, when this signal when this switch is open then the digital circuit is entrusted with converting the analog sample that it has got into the digital value and the sampling rate it should not be very fast. So, basically what we need is that the digital circuit should be given enough time for getting it converted into the getting the analog value converted into digital value and then only the next sample should come.

So, you can understand that if you are having a very fast varying signal then this analog to digital converter it is also going to it is also needed to be very fast and after it is converted into these digital the these samples and then this analog this sample analog samples they are quantized and encoded to get the final digital value. So, we will explain this as we proceed in this portion. So, essentially there are two parts. So, one is called the sampling and hold part and another is the quantization and encoding part. So, we will first look into the sampling and hold circuitry and then we will go to this quantization and encoding part.