Digital Circuits

Prof. Santanu Chattopadhyay
Department of Electronics and Electrical Communication Engineering
Indian Institute of Technology, Kharagpur

Lecture – 37
Data Converters

We will next look into a new topic, which is known as Data Converters. Now, as we know that any digital system that, we are designing. So, ultimately it is going to be used in the environment, while it has to interacts with the analog signals. Like if we are looking into say a temperature controlling system. So, the temperature is an analog value and there are sensors which will be sensing the temperature. And that that sensing will convert the physical signal into some electrical signal. So, it may be converting the temperature value into some current or voltage value, but that is an analog value.

But, in case of these computers that we have so; they can process only digital value. So, we have to convert it into some digital value. So, that way there may be some error introduced in the process like, may be when the temperature is forty degree Celsius. So, it output some voltage. So, if it is expected that say from 40 to 45. So, next temperature sense is 45. So, according the voltage value increases.

So, then that conversion to digital from this voltage to this digital value, so, that should be equivalent if we are going from say 20 to 25 degree change. So, the amount of 5 degree change that we have the corresponding if the sensor that we have so, it gives the good reflection of it in terms of analog signal, analog voltage. And if we assume that the analog signal change is equivalent to the change in the physical signal, then from this analog signal to digital signal conversion that should also be proportional.

So, we need to have some special circuitry that we will be doing this conversion of data like when the computer wants to read some analog value from the environment. So, it has to be some it has to be converted from analog to digital. Similarly, if the computer wants to control some system; so by giving some electrical signal to so, for example, some motor has to be rotated. So, motor has to be given some voltage which it will understand at which speed it has to rotate.

But, this computer cannot output the voltage directly so, analog voltage directly. So, it will output some digital value and then the digital value has to be converted into analog signal before giving it to the motor. So, these type of data converters are necessary, when we are interfacing it is digital system with the environment.

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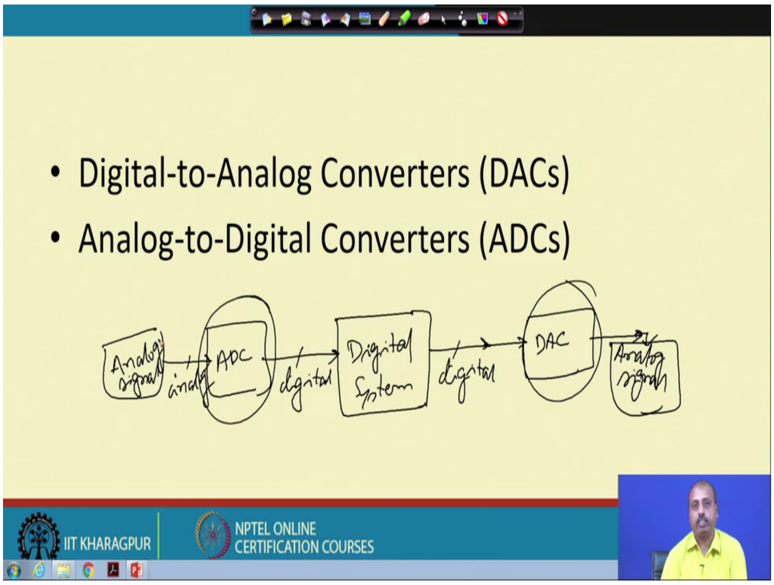

So, in this part of the course so, we will be looking into 2 such converter mechanism one is called digital to analog converter or DAC, and another is known as analog to digital converter or ADC.

So, we can say that a typical diagram for this entire system is like this that we have got this as the digital system. So, this is the digital system that we have and from the outside worlds. So, we are getting the analog signal, we are getting the analog signal and it passes through something called analog to digital converter. So, this is the ADC and then these value is the digital. So, this is the digital value that we have and here we have got the analog value.

And, after doing the processing this digital system it outputs some digital value. And, that digital value has to be converted to analog before it is given to the environment. So, this is 1 digital to analog converter and then this is the analog signal. So, this is the analog signal that we get ok. So, this is how this whole system will work. So, we need to understand this 2 circuitry DAC circuitry and ADC circuitry, because they becomes a very important part of the this interfacing this digital system to the analog environment. So, how do we do that so that we will see?

Now, the first they are 2 distinct type of converter.

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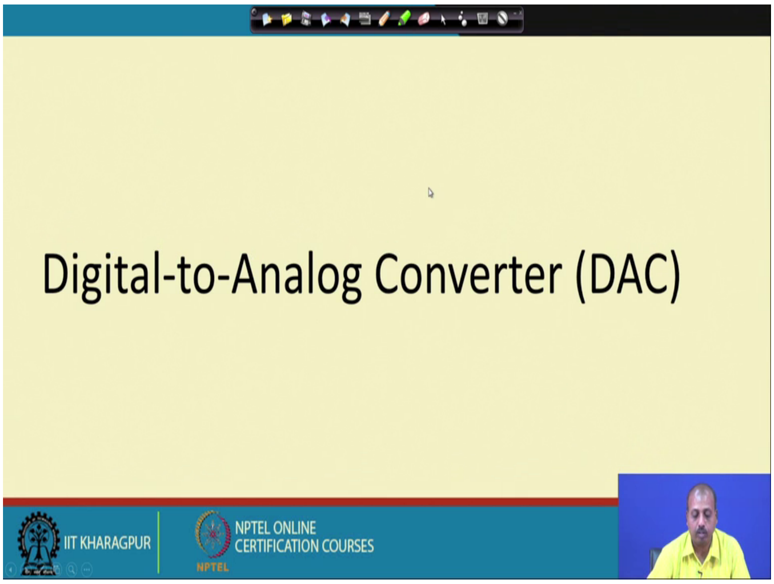

So, we will first look into the digital to analog converter which will convert the digital signal to the analog output.

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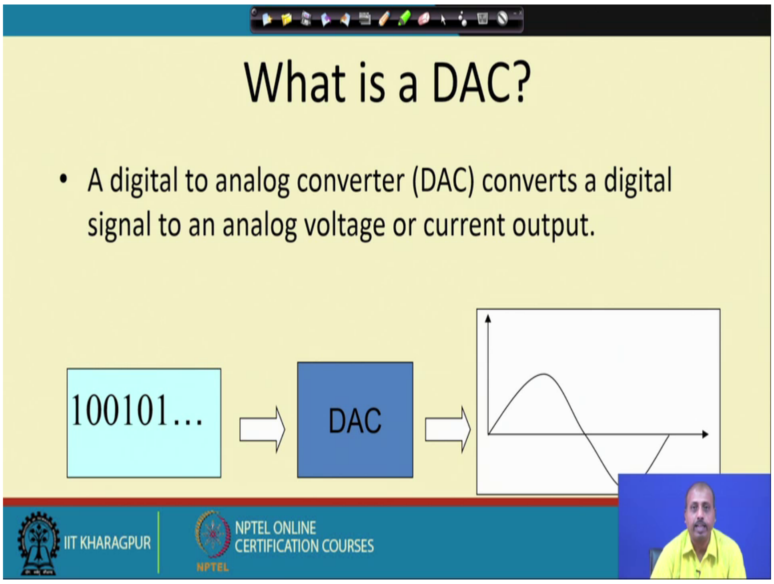

So, what is DAC? A digital to analog converter it converts a digital signal to an analog voltage or current output. So, because voltage and current they are they do not cause much of problem, because if we get a current output also so, we can pass it through a resistance and then measure it the corresponding voltage. So, as a result is current and voltage. So, these 2 outputs any of these outputs are with us.

So, if you give some if this is the digital to analog converter block and you were giving an input like say 1 0 1 0 1 etcetera some bit pattern is fed. So, it is expected that it will be outputting some analog signal. So, it may be some for the sake of understanding. So, I have drawn a sinusoidal signal here, but it may be it is definitely dependent on the bit pattern that your feeding here, accordingly you can generate some analog signal this point.

Of course, you can you can feed this bit pattern in such a fashion, that the output signal is a sinusoidal signal or a square signal or a triangular signal, whatever we want; so whatever control signal is needed for controlling the device that is connected to this analog signal. So, we can produce that signal accordingly.

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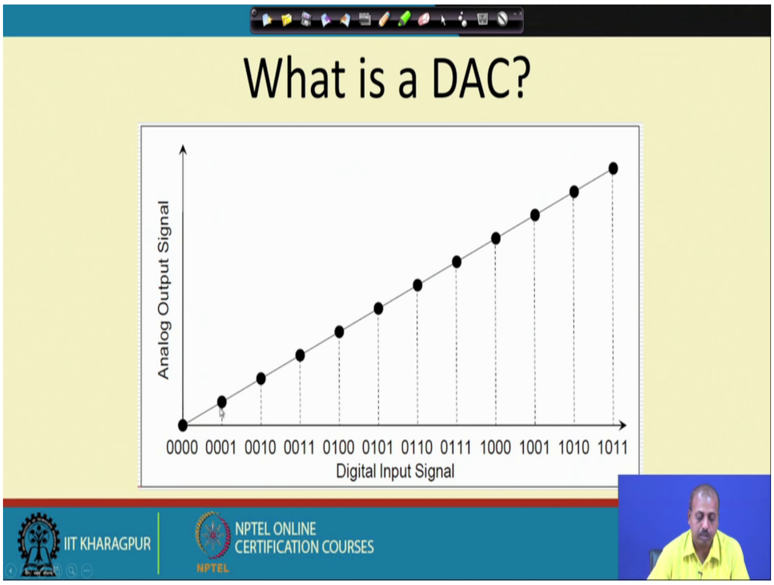

So, so, this is the digital input signal. So, there may be we are outputting from 0 0 0 0 to 1 0 1 1 and on the analog output signal. So, it increases like this. So, when it is a 0 0 0 0. So, output is also 0 when the input is 0 0 0 1. So, output is this much 0 0 1 0 output is this much. So, this is the behavior of the DAC. So, at this count values 0 0 0 0 0 0 0 1 0 0

1 0 so, it will be outputting this corresponding voltages. Of course, it is not a continuous signal because in between what happens so, these points are not known. So, this is basically by means of some approximation we can we can visualize it as a continuous signal like that.

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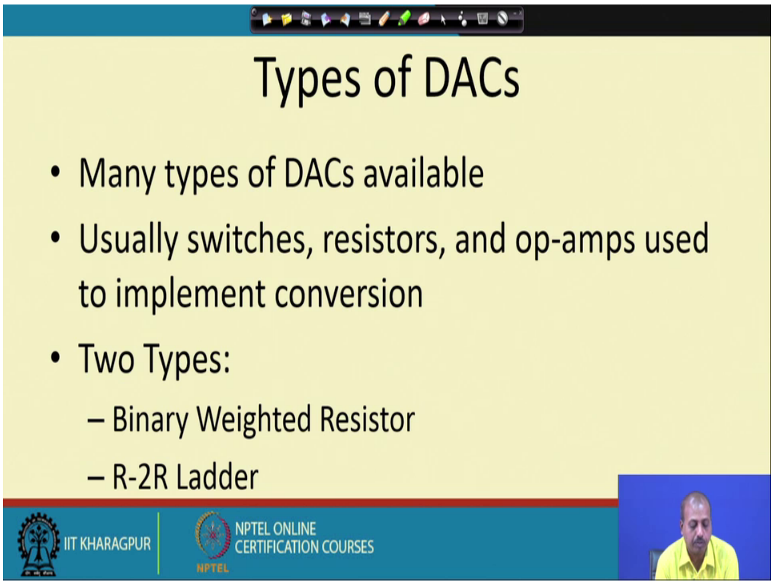

Now, if you look into these types of these digital to analog converters. So, there are many types of DACs that are available. And, they are usually switches resistances and operational amplifiers; they are used to do this conversion. And, there are we will be looking into 2 type of DAC one is known as binary weighted resistor and R 2 R ladder type resistor.

So, as I said that the main components of a DAC, they are switches, resistances and some operational amplifiers they will be used for getting the analog output.

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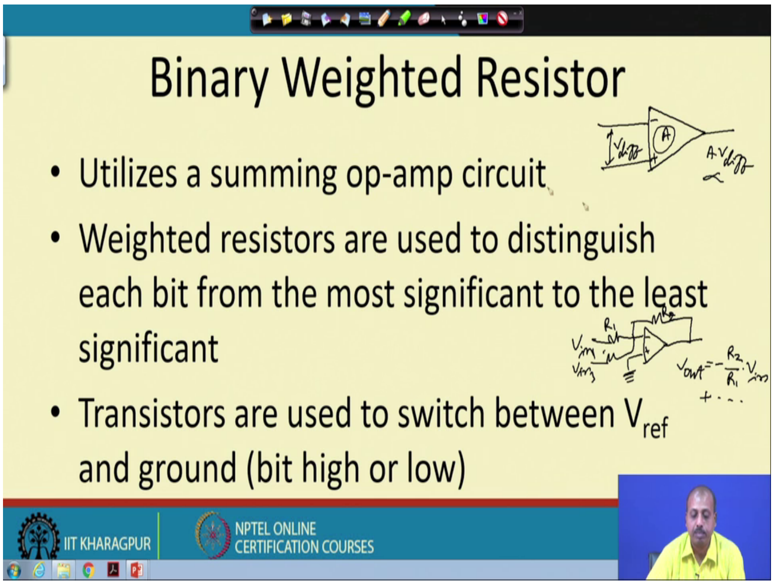

The first binary so, first digital to analog converter that we look into is the binary weighted resistor based digital to analog converter. So, you utilizes a summing operational amplifier circuitry. So, what we mean by a summing operational amplifier is so, operational amplifier is some circuit like this I hope your familiar with the this diagram.

So, basically the some input is given it takes a differential input and this amplifier has got a gain of A. So, what is the difference between these 2 voltages if we call it V diff, then the output is a into V diff. So, ideal operational amplifier this A is infinity. So, this value will go to infinity. So, if on the other hand we can have some feedback to control the gain and as you know that there are 2 types of inter 2 types of organizations of this amplifier for using op amp.

So, one is called inverting amplifier, another is called non inverting amplifier. So, this they have got particular gain expression which is less than infinity. For example, if we are having this inverting type operational amplifier. So, the circuit diagram is like this.

So, if we apply V in here and then if this resistance is say R 1 and this resistance is say R 2, then this V out value is given by minus of R 2 by R 1 into V in. So, from this infinity gain so, we can restrict we can control this gain of the circuit. Now, this type of so, if I have got a number of voltage sources. So, V in 1 then V in 2 V in 3 like that. So, they can be added here, the successive turns can be added here, and then it give rise to something called this summing operational amplifier. So, we will see some circuitry on that.

However, these weighted resistors are used to distinguish each bit from the most from the most significant to the least significant bit. So, each bit we will contribute to some value for into the output. So, most significant bit it is contribution will be high, that is if the most significant bit is one. So, it will contribute significantly to the output voltage or current. So, if we will go down and look in to the successive bits their contribution will be less and lesser and lesser.

So, the least significant bit it will have the minimum contribution and that way it will go. So, transistors are used to switch between V ref and ground, which is bit high and low. So, V ref is the reference voltage, which is which is taken this high value and low is the ground. So, that is taken as the 0 value.

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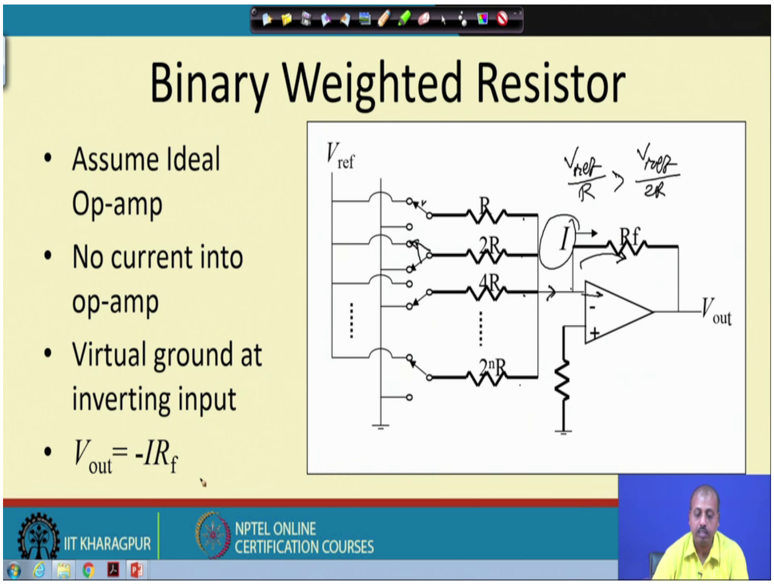

So, this is the structure you can say. So, each of this bits that we have so, each of this lines so, they constitute 1 bit fine. So, you can see that we have we have got we have got this operational amplifier like this bit. So, if it is a so, this bit. So, if I connect it to this point. So, this V ref the current that is drawn by drawn by this is V ref divided by R.

So, similarly when it is when this switch is connected to say this point then the current drawn will be V ref divided by 2 R. So, as a result the contribution from the first if this switch is connected here that the contribution that is coming on to this line is the current value is V ref divided by R. And, if we connect this line to here if it is connected like this in the contribution is V ref divided by 2 R.

So, this contribution is less than this one ok. So, as you go down and down. So, what happens is that this contribution becomes exponentially less. So, whatever be the contribution here current contribution. So, this has got half of that this has got half of that. Finally, the nth bit it will have the contribution reduce by a factor of 2 to the power n. So, if we assume this operational amplifier to be an ideal operational amplifier. So, no current flows into this op-amp. So, whatever current comes like this it passes like this fine.

So, you can say that V out is given by I into R F. So, V out is given by I into R F. So, we can try to figure out what is the value of I and based on that we can find out what is the voltage that is coming as the output. So, let us see.

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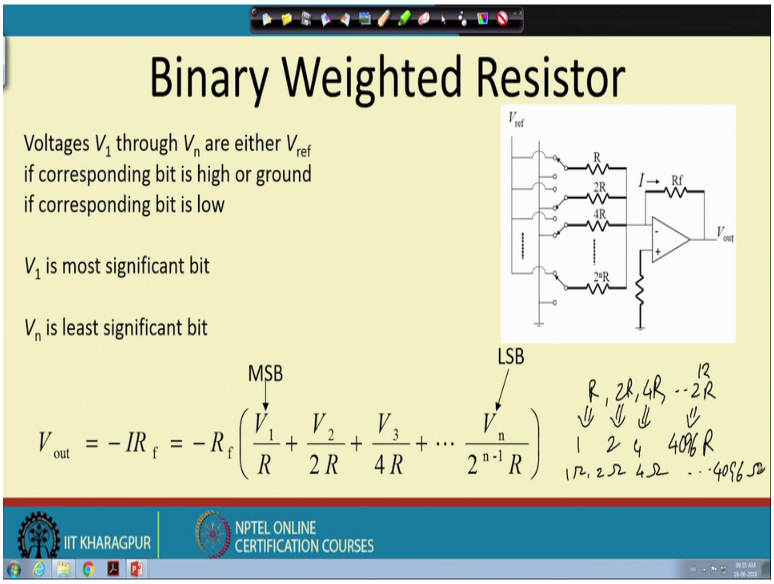

So, this I was telling this I into R F. So, this expression for I. So, it has got this V 1 by R for the most significant bit V 2 by 2. So, V 1 is the most significant bit. So, it is and V n is the less least significant bit.

So, whatever we coming here as voltage; so this is given by V 1 by R so, at this point if the voltage is V 1 so, it is V 1 by R, second one is V 2 so, it is getting V 2 by 2 R then, third one is V 3 so, V 3 by 4 R, last one if it is V n. so, V n by 2 to the power n minus 1 into R. So, this is so, this way it is reduced. So, this should be 2 to the power n are not 2 to the power n minus R n minus 1. So, this is so, there are n such cases. So, it is like this so, V n is the least significant bit and then it is V n divided by 2 to the power n into R.

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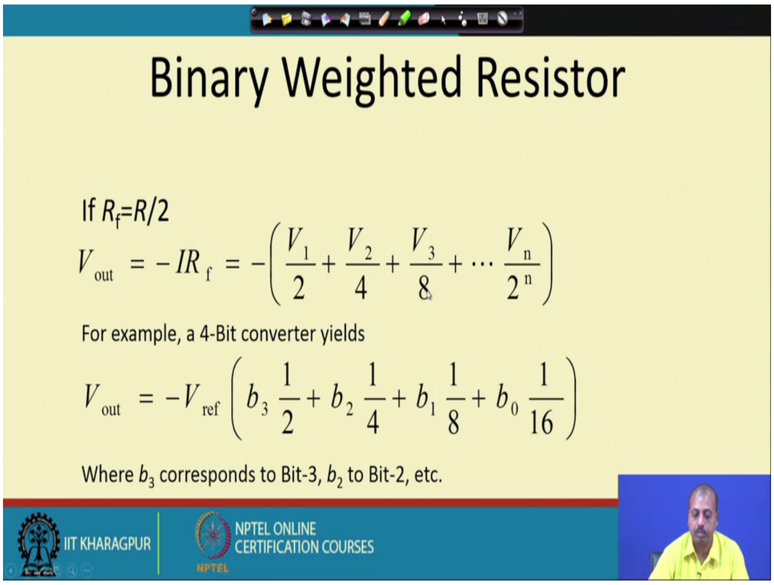

Now, if we so, if R f equal to say R by 2. So, if you take R f equal to R by 2, then this V out equal to minus I into R f which is V 1 by 2 plus V 2 by 2 plus V 3 by 8 up to V n by 2 to the power n. So, then we can say that this if you have got say 4 bit converter, then this V 1 is nothing, but V ref this V 1 V 2 V 3 they are all equal to V ref. So, this V ref is taken out.

Now, depending upon this b 3, b 2, b 1 and b 0 this bit pattern so, this contribution will be coming. So, you can say in this diagram you see that if I connect this point to here then V 2 becomes equal to 0. If, I connect this point here then the V 2 becomes equal to V ref ok. So, that way we can say that this V 1 V 2 these voltages can be either equal to V ref or equal to 0 and that is controlled by the position of this switch.

So, when the switch is connected to this we can say that the corresponding bit is equal to 1 and when the switch is connected to this position so, we can say the corresponding bit is equal to 0. So, here if I take say b 3 equal to 1 that is the most significant bit is connected to is equal to 1. So, it is getting the contribution V ref V 1 equal to V ref in that case. So, in the second one if b 2 is not second bit is do not connected. So, b 2 is second bit is second switch is connected to ground so; that means, b 2 is equal to 0.

So, in that situation this b 2 being equal to 0 so, V ref contribution does not have anything to here V 2 becomes equal to 0, so because of this b 2 into V ref, so b 2 being equal to 0 so, this the value of V 2 becomes equal to 0. Similarly if the third bit is equal to 1 then this V 3 becomes again equal to V ref and if this nth if the least significant with b 0 is equal to 0, then this contribution b 4. So, that will become equal to 0.

So, b 3 corresponds to b 3 b 2 corresponds to b 2 like that. So, that way we can have a binary weighted resistor based structure for getting this V out. So, depending upon the digital value that if b 0 b 1 b 2 b 3 value of V out will get determine.

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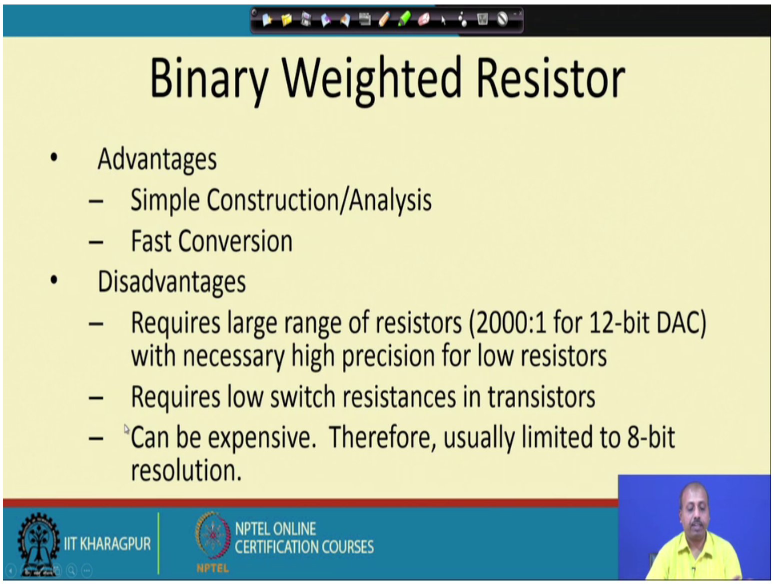

So, what are the advantages? So, it is a simple construction and analysis. So, simple because you just need a couple of resistance resistances and then connect it is some fashion. Conversion process is quite fast, because it is all the comparisons are being done simultaneously. So, the conversion process is also fast, but there are disadvantages because requires large range of resistors like for 12 bit DAC. So, for 12 bit DAC, so, we can understand if we look into this diagram. So, this is going from. So, it is going from R 2 R 4 R up to 2 to the power 12 R ok. So, 2 to the power 12 is 4 0 9 6 R.

So, if you take even if you take R equal to 1 ok, if you take R equal to 1 then this is equal to 2. So, this is equal to 4. So, you need all these resistors like 1 ohm resistor 2 ohm resistor 4 ohm resistor so, like that up to 4 0 9 6 ohm resistors. So, getting resistances of this exact values is a problem or getting resistance is in this ratio is also a problem. So, that makes it difficult for this realization of this binary weighted DAC ok.

So, with necessary high precision of low resistors so, it is difficult requires low switch resistances in transistors. So, these transistors that, we have taken. So, these resistances actually coming so, this switches they are actually realized by some transistors like if it is a moss transistor.

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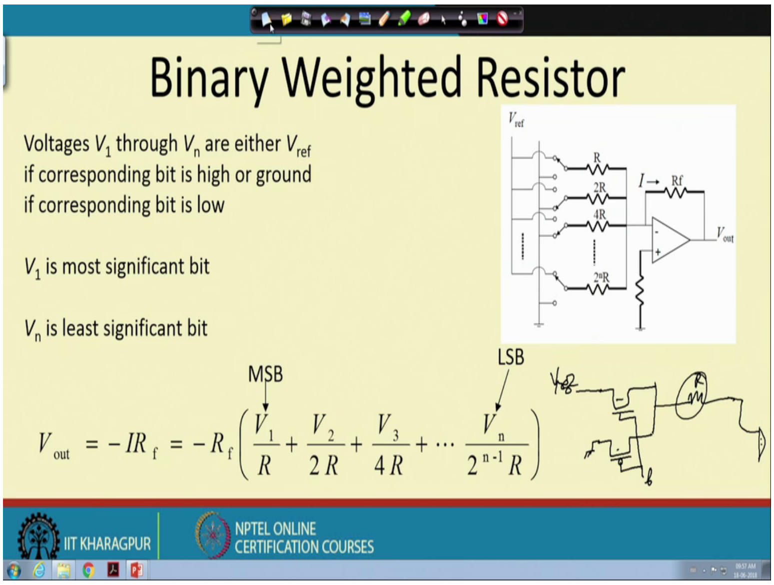

So, this is if the connection is like this. So, this point is connected to V ref this is connected to ground and we have got a switch. So, this is connected to the digital bit V.

So, if V equal to 1 then V ref gets connected here if V ref b equal to 0 then this ground gets connected here. So, if the problem is that this channel resistance that also comes in the series in series with the resistance. So, here I have got that R resistor. So, this is the R resistor finally, going to this side and finally, going to that op-amp. So, this channel resistance is they will come in series with this R resistance. So, with this channel resistance it should also be pretty low. So, that we do not have we do not have problem in getting the proper resistance values implemented.

So, that is the point. So, this switch resistance is should be low. And, it can be expensive because of this we have to getting this resistances of good precision particularly, the resistors which have got low values getting them is good high precision may be costly. Therefore, so, it is usually limited to 8 bit resolution you do not go for 12 bit and all. So, normally keep it within 8 bit resolution.

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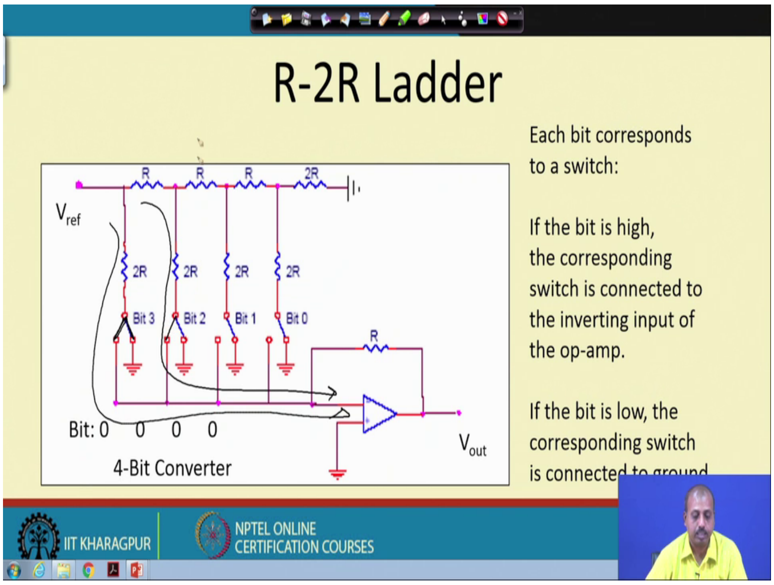

Another type of DAC, which is pretty common, which is known as R 2 R ladder; so here you need only 2 types of resistors 1 is of value R, other is a value 2 R. So, unlike the previous case where you were requiring a series of resistance values so, here that is not required. So, you require R 2 R ladder type of R R and 2 R resistances and they are connected in this fashion. So, from V ref we make it R R R and finally, there is a resistor 2 R. And so, so this is a 4 bit converter. So, we have got 3 such resistance R in series and then 2 R resistor in series and then from this point. So, we take down take the 2 R resistance and take it down.

Now, this depending upon the bit configuration so, either this is connected to ground or it is connected to this one this. So, this is a point which is it may be connected to this point or it may be connected to ground. So, these switch so, either it is connected here.

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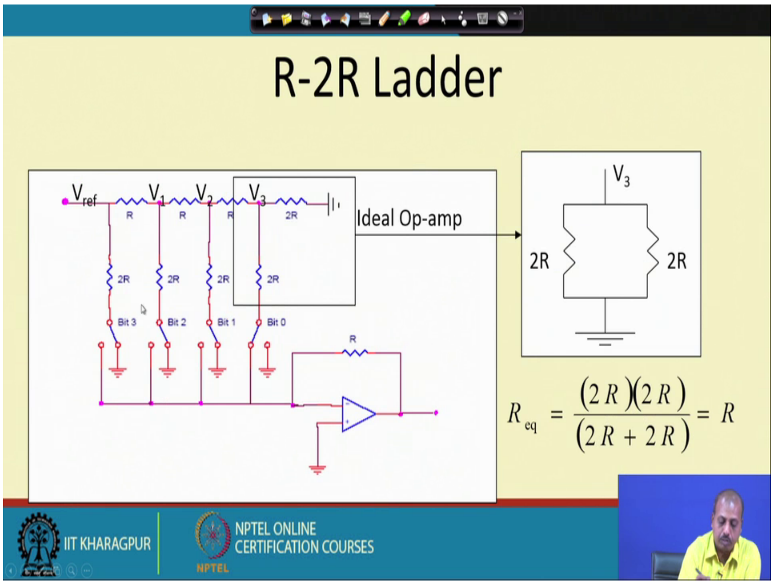

So, this sorry; so this point so, it is either connected to this or it is connected to this. So, when it is connected to this; that means, is 0 is coming here, if it is connected to this then the contribution, the current flow contribution actually so, either the either the connection is like this or the connection is like this.

So, if it is connected like this then there is no contribution of this bit. And, if it is connected like this then, it is this current flows in this fashion. Similarly, for the second bit may be it is connected like this. So, as a result this does not have any contribution no current contribution is coming, but if it is connected in this fashion then again a current contribution like this will come.

So, then it is a summing type of structure. So, that is all right. So, each bit corresponds to a switch if the bit is high the corresponding switch is connected to the inverting input of the operational amplifier, if the bit is low the corresponding switch is connected to the ground ok. So, it is in this fashion it is connected ok.

So, so, this is the switch. So, either it is connected to the inverting input of the op amp like this or it is connected if the bit is low then it is connected this is switch is connected to the ground. So, this way this connection is made. Now, so, let us see how it works fine? So, so, if we look into say this part then what is happening is that this V 3 voltage? So, there is a 2 R 2 R. So, these 2 resistances are there. So, they are in parallel. So, R equivalent is equal to R for this part. So, the equivalent when this bit is connected like this. So, some part of the current will flow like this some part of the current will flow like this. So, you will get R equivalent equal to R.

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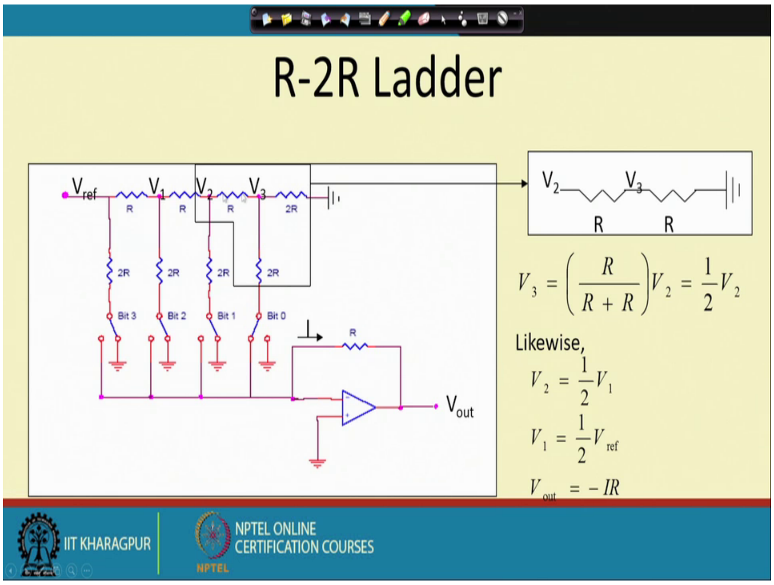

So, now if you consider this V 2 ok; so, V 2 after that we have got this R then V 3 then this part is equivalent to R as we have seen previously so, this part is equivalent to R. So, this equivalent will the V 3 becomes half of V 2. So, V 3 is equal to half of V 2. In this way if we continue then V 2 will turn out to be half of V 1 V 1 will turn out to be half of V ref and V out is equal to minus I into R. So, that is there. So, once you have got these values of V 1 V 2 and V 3. So, you can find out what is the value of I and accordingly you can get the V out value.

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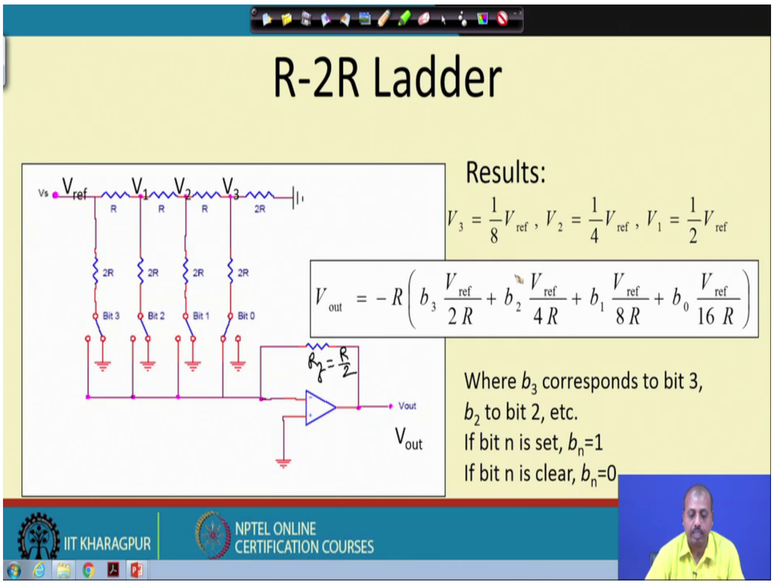

So, for example, in this case we have got V 3 equal to V 3 equal to 1 8 of V ref. So, so, V 1 is half of V ref so, V 1 is half of V ref V 2 is half of V 1 that is one-fourth of V ref and V 3 is half of V 2 that is one-eighth of V ref. So, this way we get it like this. And then when this summing is done when this summing is done then it is becomes minus R into b 3 into V ref by 2 R plus the b 2 into V ref by 4 R plus b 1 into V ref by 8 R plus V 0 into V ref by 16 R, so by taking this R equal to this feedback equal to half of R by 2.

So, in this structure, so, it is assumed that this feedback resistance this R f equal to R by 2, that is why this expression becomes like this ok. So, b 3 is connected to so, you so, b 3 is connected to b 3 b 2 is bit 2 etcetera. So, if bit n is set then b n equal to 1 and if bit n is clear then b n equal to 0.

So, in this fashion we can have an R 2 R ladder implemented and it gives the corresponding digital output.

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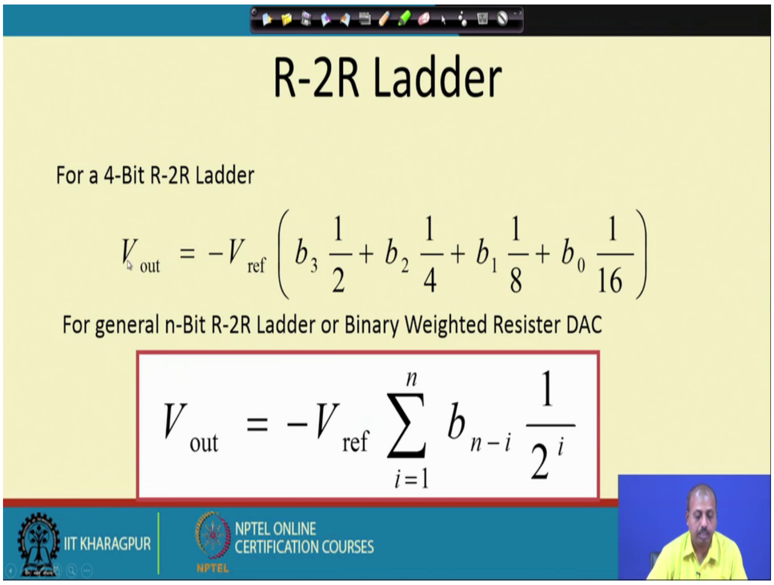

So, we have got this V out is this is the final expression that we have. So, V ref into b 3 into 1 by 2 so, this taking that R f equal to R by 2. So, we get it V ref equal to b 3 into 1 by 2 plus b 2 into 1 by 4 b 1 into 1 by 8 plus b 0 into 1 by 16.

So, for general n bit R 2 R ladder and or binary weighted resister and DAC so, the equation becomes V out equal to minus V ref into sigma I equal to 1 to n b n minus I into 1 upon 2 to the power I. So, this is the final expression for any DAC circuitry that we have which converts from digital to analog value.

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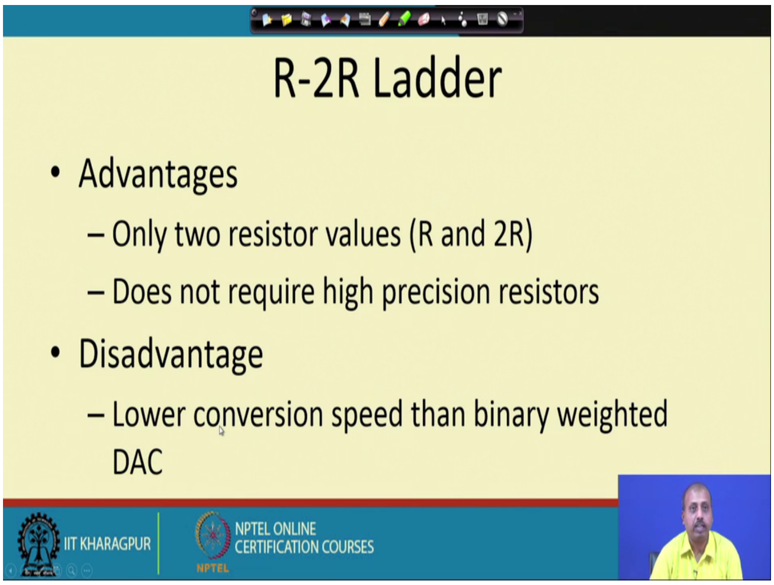

So, why should we go for R 2 R ladder? So, advantage is the only 2 resistor values are necessary which is R and 2 R and does not require high precision resistors.

So, only thing is that you need for getting 2 R. So, what we can do we can take 1 resistance 1 type of resistance are connect 2 of them in series. So, we get 2 R. So, ideally we can say only single resistance is sufficient and you can just sometimes connect two of them sometimes connect one of them, to get the R 2 R configuration or you can get the exactly double of the resistance 1 k and 2 k and that way we can connect it.

So, disadvantage is the low conversion speed then binary weighted DAC.

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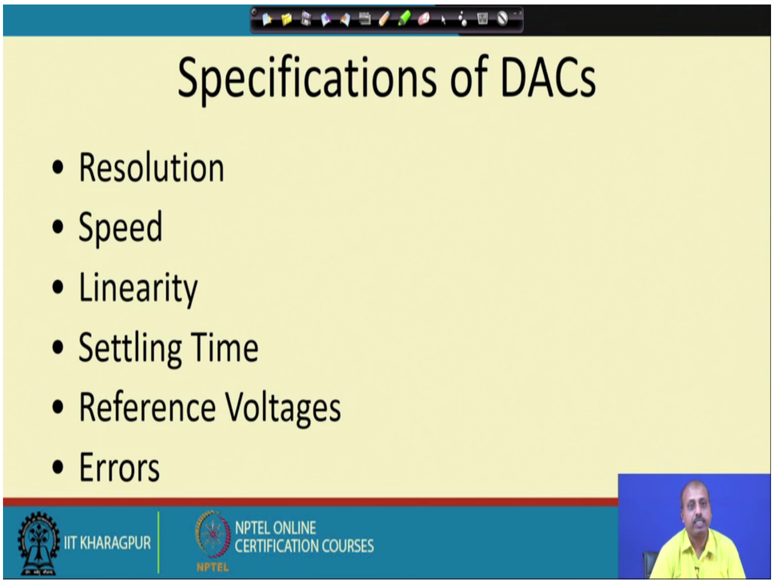

Because, of this current this voltage being decided by individual resistances and then so, it becomes lower compare to this binary weighted DAC. When, we are talking about specification of a DAC. Now there are several DAC that may be available in the market, like if we are looking for a particular type of DAC. So, what are the factors that you should talk about?

One thing is the resolution then the speed then resolution will come to this term then speed of conversion, then how much linear it is in the settling time reference voltage and error?

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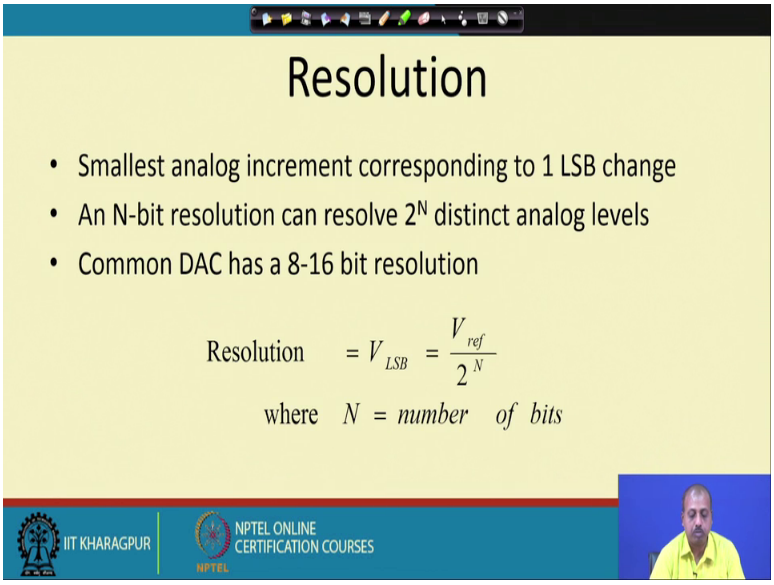

So, will look into this issues, then resolution it says the smallest analog increment corresponding to 1 LSB change.

So, the minimum amount of change that DAC can do is by changing the LSB. So, if you change the least significant bit from 1 to 0 or 0 to 1 there will either be increase or decrease in the analog outputs. So, when you do this change then what it is the corresponding analog voltage change? So, that is the resolution. So, you cannot change the analog voltage by a value which is less than this one. So, that is the resolution.

N bit resolution can resolve 2 to the power N distinct analog levels and basically from 1 bit once a bit sequence to the next bit sequence next digital count binary sequence, if you go then what is the minimum change in the analog voltage. So, we cannot go change behind that. So, if we have got the reference voltage as V ref then if no, that there are 2 to the power N distinct analog levels that you can have.

So, the resolution is given by V ref divided by 2 to the power N. So, which is also known as the voltage corresponding to L S B V L S B so, this is the expressions for the resolution of the DAC, where N is the number of bits. So, common DAC they have got 8 to 16 bit of resolution because for higher resolutions I have to go for more number of bits and then the constructions of the DAC becomes difficult. So, normal DAC is we go for 8 to 16 bit of resolution. And depending upon the V ref we can get the final analog voltage value by which it can change.