Principles of Mechanical Measurement

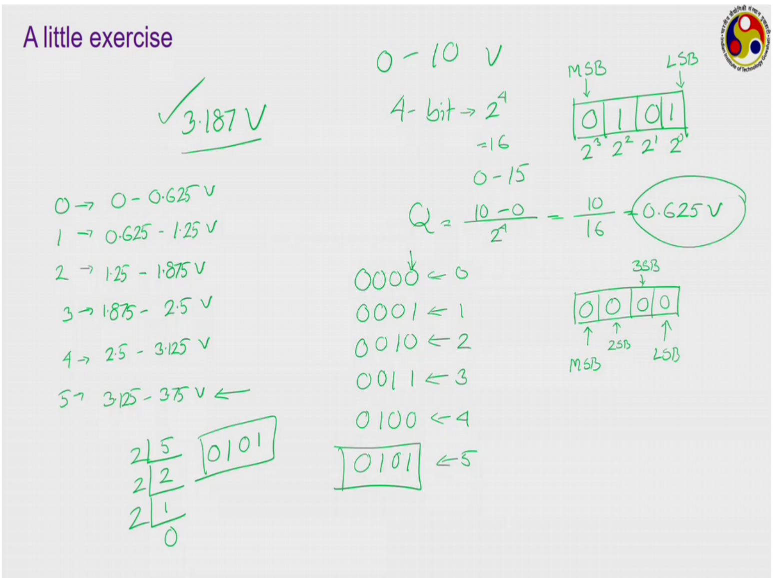
Dr. Dipankar N. Basu
Department of Mechanical Engineering
Indian Institute of Technology, Guwahati

Module – 03
Digital Techniques in Measurement
Lecture – 4
Digital-to-analog conversion

Good morning friends, we are back with the fourth lecture for our week number 3 where we are talking about the application of Digital Techniques in mechanical measurement. In fact, I am telling good morning because I am recording this video in a very cold and wet morning at Guwahati, but you may be seeing this one it some other time. So, please alter the initial introduction that way means. Now in the earlier 3 lectures, we have mostly covered all the relevant topics apart from only one which is left for today's discussion.

We have discussed about the number system, we have discussed about the importance of digital transmission over analogue transmission, we have discussed about why binary is generally preferred over other number systems like decimal octal or hexadecimal, then we have seen the use of logic gates and their combinations to transmit the data or to modify the binary data and in the last lecture where we have discussed about different methods of converting an analogue signal to its digital counterpart. Today we shall be discussing the other of that other version or the other extreme of that is converting the digital signal to its analogue counterpart. But before that like we always keep on doing let us do a little bit of exercise based upon what we have already discussed in the previous lecture.

(Refer Slide Time: 01:55)



So, in the previous lecture, we have discussed about converting an analogue signal to digital signal using different kinds of devices. We have talked about the digital ramp ADC, the integration based ADC single slope or double slope, successive approximation ADC, sigma delta ADC and also the flash ADC. Each of them having their own advantages and disadvantages a. Let us take one example of an analogue signal and see how we can convert this to a digital signal or what will be the corresponding digital signal.

One thing you must keep in mind, it does not matter what kind of conversion system or what kind of ADC s you are using. As long as the resolution of the instrument is same the analogue output should also sorry the digital output corresponding to the analogue input should also be the same. Let us we have dealing with the device which is having a voltage range of 0 to 10 volt and it is a 4 bit device that; that means, whatever analogue input you provide within the range of 0-10 volt that will be represented by a 4 bit binary number. It is a binary number which can compress of 4 digits.

This is the way we represent the bits where the first one corresponds to the least significant bit or 2 to the power 0, then this is 2 to the power 1. This corresponds to 2 square, this corresponds to 2 cube. Here this one is the least significant bit. This one is the most significant bit. So, it does not matter I repeat what kind of device you are using, but you should get the same binary output. Then let us say the input that we are providing is 3.178 volt and somewhat randomly we have chosen a value, then what should be the digital counterpart corresponding to this that we have to identify.

So, fast can you decide what is the resolution of your converter range is 0 to 10 volt that is maximum voltage can be 10 minimum voltage is 0 and its 4 bit 4 bit means how many total number of levels it can have it can have 2 to the power 4 that is total 16 level that is starting from 0 to 15. These are the different levels it can have and you have to identify this input value of 3.187 falls in which one then accordingly we can get its digital counterpart. Now the resolution of this one Q should be the maximum voltage minus minimum voltage divided by 2 to the power 4 that is 10 divided by 16 which is 0.625 volt.

So, width of each such level should be 0 point sorry 0.625 volt and then we have to identify exactly where it should fall. There are we can identify it in say very crude way, we can go in more systematic pattern. Crude way means let us say the first level corresponding to level 0, what should be the voltage corresponding to this? It should be 0 to 0.625 volt then level 1 corresponds to 0.625 to the double of this one that is 1.25 volt. Level 2 should be 1.25 to 1.875 volt, then level 3 it should be 1.875 to 2.5 volt, level 4 it should be 2.5 to 3.125 volt.

Note each of them is having width of 0.625 volts. So, according starting from 0, we just have to keep on adding this point 6 2 5 and we can identify the starting and finishing point of each of these levels. Now come to level 5, it is starting from 3.125 and it is going up to 3.75 volt and our objective is 3.187 which falls right here; that means, it should belong to the level number 5, then we can identify the binary value corresponding to this 5 digital value or decimal value and that should be a binary output.

So, what is the binary correspondence to 5? 5 divided by 2, you are getting 2 left 1, then divide 2 by this l f 1; reminder is 0. Then divide 2 1 by 2 your getting 0 left to 1 and to get the 4 bit representation add another 0. So, this should be the binary value; that means, you should get 0101 as the output for this.

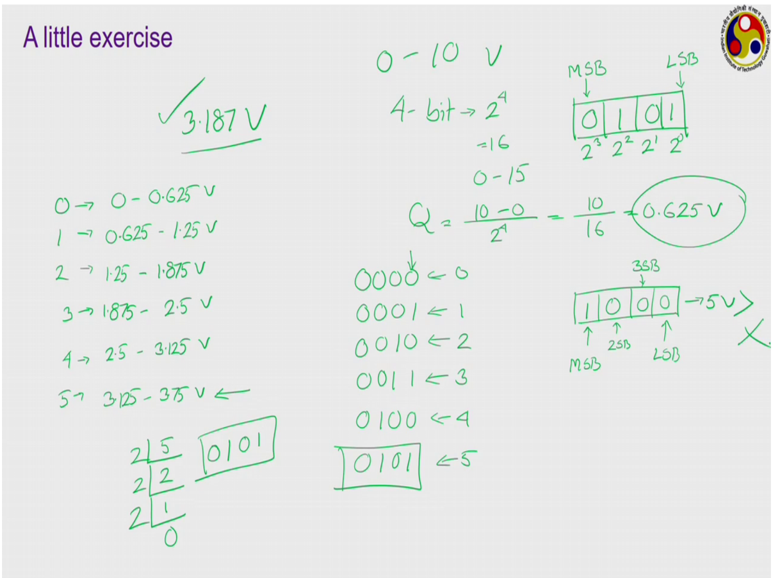
However, this is a very crude way of calculating. If you think about any particular kind of converter any particular kind of DAC, then how can you achieve this? The one that we have done here that is somehow or somewhat that is the way the digital ram one goes off that is it keeps on changing the binary value by free running binary counter and then it keeps and compares the corresponding output voltage with the actual input and then gives a then finally, settles to a particular value.

Like if this conversation we are getting using a dynamic ram converter, then it should be starting from 0000 and whatever is the corresponding voltage, it will compare with this; it is not matching this is smaller. So, it will change the least significant bit, it is still not matching; then it will go to the next one which is this, then the next one which basically it is our level number 0, this is our level number 1, this is level number 2, this is level number 3.

Whenever it is getting one binary number from its resistor, it is converting this digital value to the analogue value and comparing that analogue value to the actual input which is this one. As long as this the output from the digital to analogue converted value is less than the actual input, it will keep on changing. So, next value should be 0 1 0 0 which corresponds to level number 4. It is still not matching, then it changes this which is level number 5 and now it gets a value basic at the value corresponding to this one will be coming as to be within the range of this 3.187 volt or rather I should say that 3.187 volt will come within this range and so, it will settle this to this value.

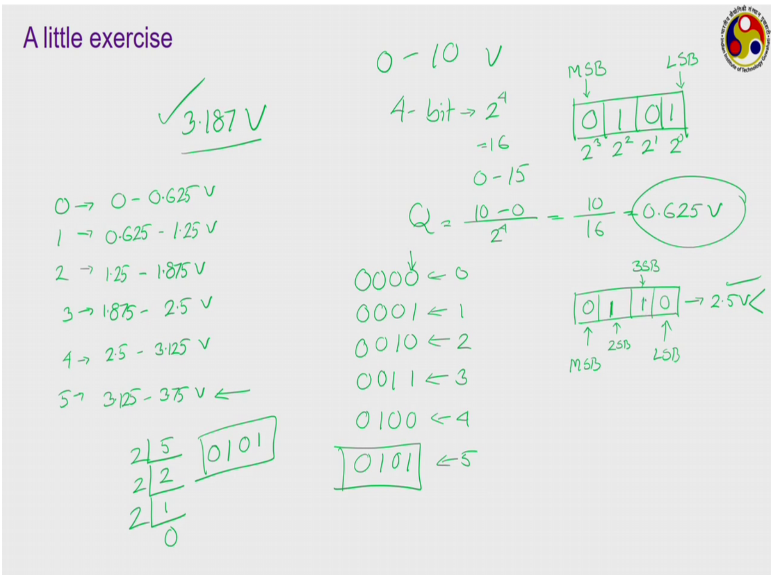
This is how a dynamic ram 1 goes on; however, as if we think about a successive approximation DAC or ADC successive approximation ADC, then how it works? It starts from the most significant bit whereas, here we are starting from the least significant bit; here we shall be starting from the most significant bit. So, the most significant bit will be set as 1, others will be set as 0 or let me do this way. Let us say this is your resistor, this is the most significant bit, this is a least significant bit. Sometimes this is called the second significant bit. This is called the third significant bit, but not that much important this terms the MSB and LSB are more important. So, initially all of them are set to 0.

(Refer Slide Time: 09:41)



Now the when the process conversion process starts, resistor will convert the value of MSB to 1 or set it to 1, then 1 triple naught corresponding to 1 triple naught. What should be the value? The corresponding value is 5 volt. Now this is greater than this 3.187. So, this is not possible. So, this was back to 0.

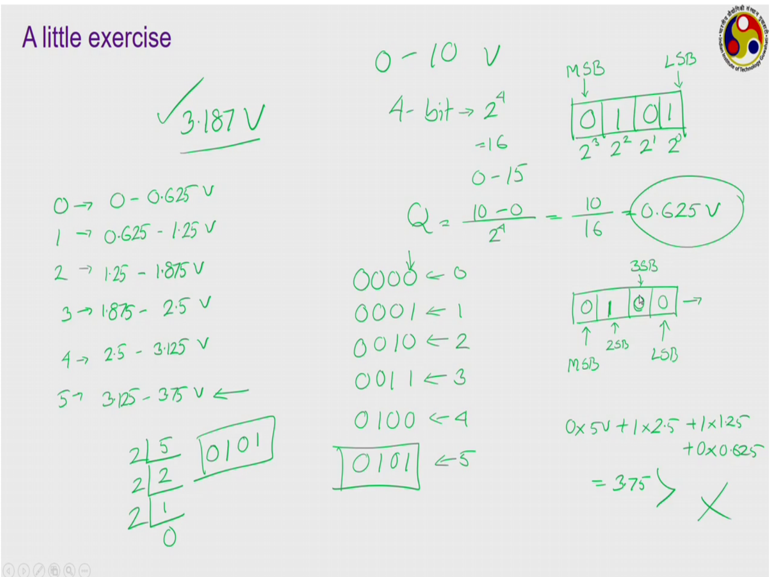
(Refer Slide Time: 09:59)



The MSB settled. Now it changes this second one to 1. What is the corresponding output value? Corresponding output value should be you know the resolution. So, corresponding value should be 2 point 5 volt. I hope you know how to calculate the voltage corresponding to this.

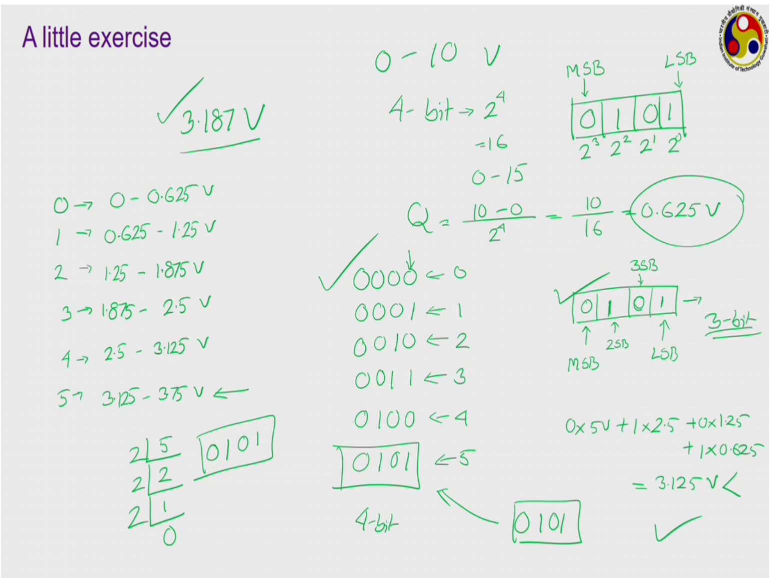
Now, this 2.5 volt is coming to be less than 3.187; that means, this is a correct one. So, we settle this one. This is settled now we move to the third one and the resistor set this to 1.

(Refer Slide Time: 10:39)



Now what should be your output value your output is now, for the first significant bit it is 0 into 5 volt or rather the most significant bit plus now the second one is finalized to 1. So, into 2.5 plus the 1 in the third which you have just set into 1.25 plus the last 1.625. So, we are getting this to be 2.5 plus1.25 that is 3.75 and this 3.75 is found to be greater than 3.187. So, this is also not correct. So, this goes off and the resistor sets this one back to 0. This is also a final. So, we have already got 3 digits or 3 bits.

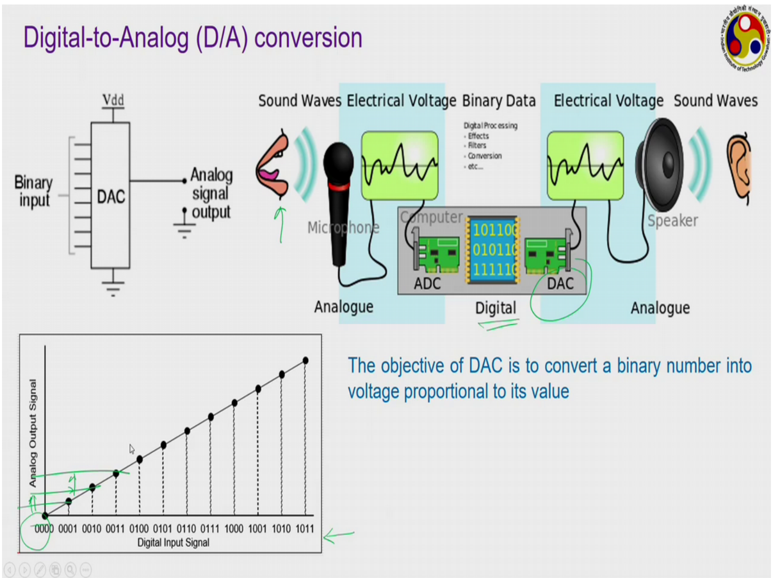
(Refer Slide Time: 11:27)



Now go to the least significant one, set this to 1; then what is the value corresponding to this? The output voltage like corresponding this binary representation corresponding digital to analogue converter will give you 0 into 5 volt plus 1 into 2.5 volt plus 0 into 1.25 volt and finally, 1 into 0.625 volt which should be 3.125 2.5 plus 0.625 is 3.125 and this is coming to be less than 3.187.

So, it will continue this value giving a final output as 0 1 0 1 which essentially the same as this one. So, this is the way digital ram converter works, this is a way a successive approximation converter works and we can they should give the same value; however, instead of having the same resolution if one of them is having say this 4 bit resolution and this one is having 3 bit resolution, definitely corresponding outputs maybe different because here it will be using 4 binary digits whereas, this one will be using 3 binary digits. But if the resolution is same the voltage ranges are same or I should say the number of bits and voltage ranges are same then corresponding binary output has to be exactly the same.

(Refer Slide Time: 12:53)



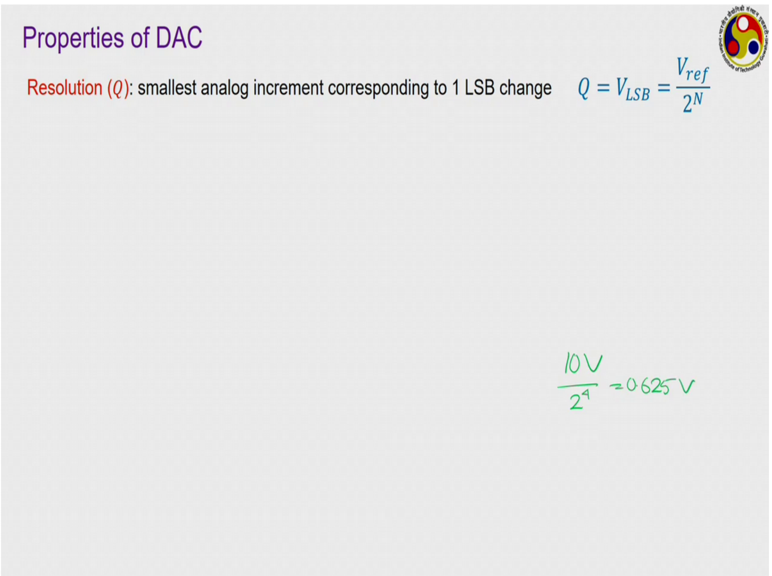
Now, let us move to the topic of our discussion for the day which is digital to analogue conversion. In digital to analogue conversion, we have a binary input which gets converted to an analogue signal output generally in the form of a voltage. So, the application of such device is probably more than the analogue to digital converter because in most of the cases when you want to store some analogue signal, we convert that to digital cases and we store it or transmit it for the corresponding advantages. However, quite often we want the final representation final output in analogue form itself therefore, whatever binary data we have stored or we have processed or we have analyzed that needs to be converted back to the analogue form and then we can get the final output from this.

Just think about one application, a very common application of a telephone receiver. When we are talking like here the sound wave that is coming out, this sound wave gets converted in the microphone to an analogue form oh sorry this analogue sound wave or analogue signal gets this sound signal gets converted to a digital form. And this digital form that gets transmitted through the wires or through whatever means like in case of mobile phones, they get transmitted via wireless connections and they goes back to the or they goes to the destination where they are supposed to reach. Now there in the hands if the digital signal gets converted back to analogue and we get the sound wave back the analogue sound wave and so, the recipient is able to hear the sound. Basically the telephone receiver so, the mobile phone receivers that we have they are they can do the both means taken convert the sound wave to the digital form there by facilitating the analogue to digital conversion.

And similarly when they are we are receiving a call or when you are rather I should say when you are hearing the sound of the person other end of the phone, then it is converting the digital signal to the analogue sound wave so, that we can hear what they are saying. This way there are several kind of applications probably infinite number of applications of digital to analogue conversion. So, the digital to analogue converters or the DACs their primary objective is to convert a binary number into voltage proportional to its value the voltage will be the voltage, we can use some suitable calibration to get the actual output that we are looking for. So, each of the binary digits should have a corresponding voltage value associated with this like say if we are talking about a binary representation with this digit like shown here then the first one if that is representing 0 then whatever distance we have it in the first and the second one.

Similarly, the same distance we should have between the next 2 and again the same distance, we should have between the next 2. So, this way each of them gives a finite value of the voltage and the objective or the entire working procedure of this DAC is based upon assigning the suitable voltage or give the suitable voltage output corresponding to whatever binary number that you are giving.

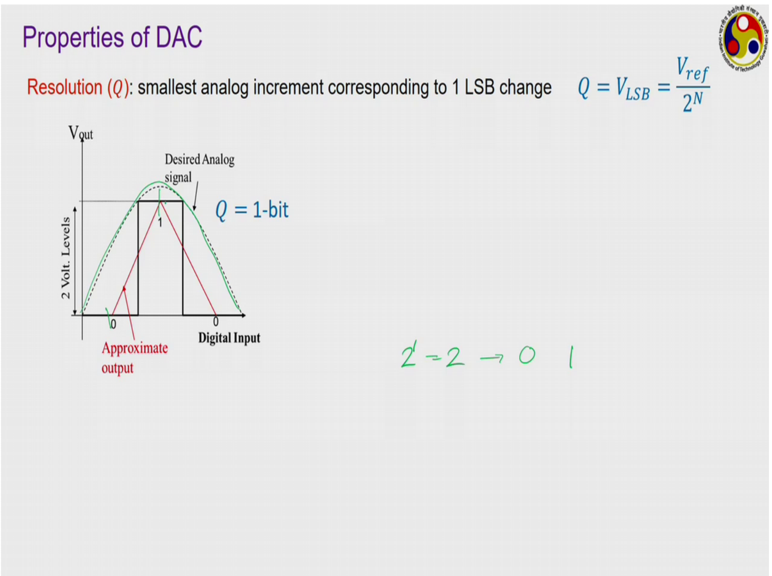
(Refer Slide Time: 16:13)



There are several properties of importance to DAC, but most of you are already known to you. Firstly, when your from our discussion of the first chapter first module where we have learnt about different properties of measurement systems and also in this week itself when you have discussed about different terms associated with the analogue to digital conversion more or less similar properties are also relevant to DACs.

First is definitely resolution refers to the smallest analogue increment corresponding to one bit change in the digital input like if there is a small 1 bit change generally in the least significant bit position, whatever change in the final output that we get that is what we refer as resolution. And quite similar to the analogue to digital converters, here also it is set to be the voltage associated with the v of the least significant bit or you can say the reference voltage divided by 2 to the power n where n refers to the number of bit. Like if the reference voltage is said to be 10 volt and you are talking about a 4 bit converter, then it will be 10 volt by 2 to the power that is 0.625 volt we that is the same way we calculate for ADCs.

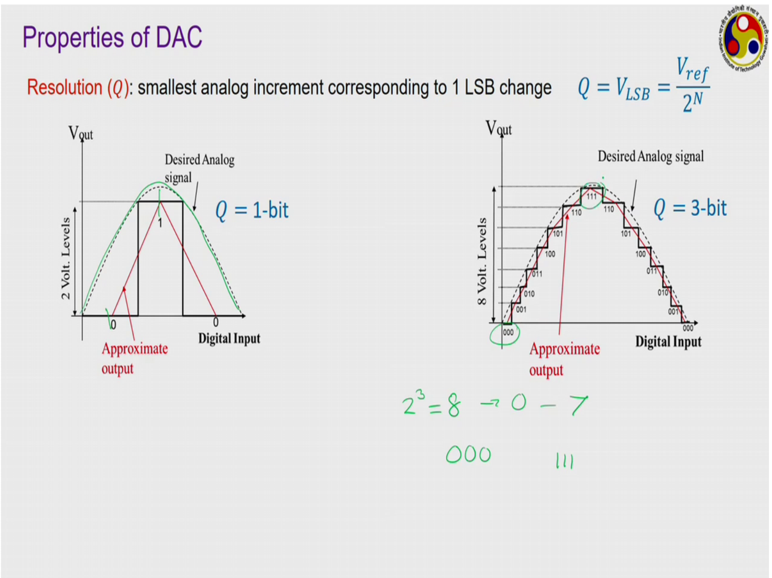
(Refer Slide Time: 17:25)



So, the it is always desirable to have higher resolution like any measurement device. We always want higher resolution; that means, with a smallest possible change in the input, we want larger change in the output; that is what the basic definition resolution is and the same is applicable here also. When you have larger resolution we always prefer to go for that device like just see this example. Here our analogue desirable analogue signal is something like a parabolic curve. This is a desirable analogue signal or analogue output which you are looking for, but as your using one bit converter then, it can have only 2 2 levels 0 and 1 because it is a 1 bit converter. So, it can have maximum 2 to the power 1 that is 2 levels which are 0 and 1.

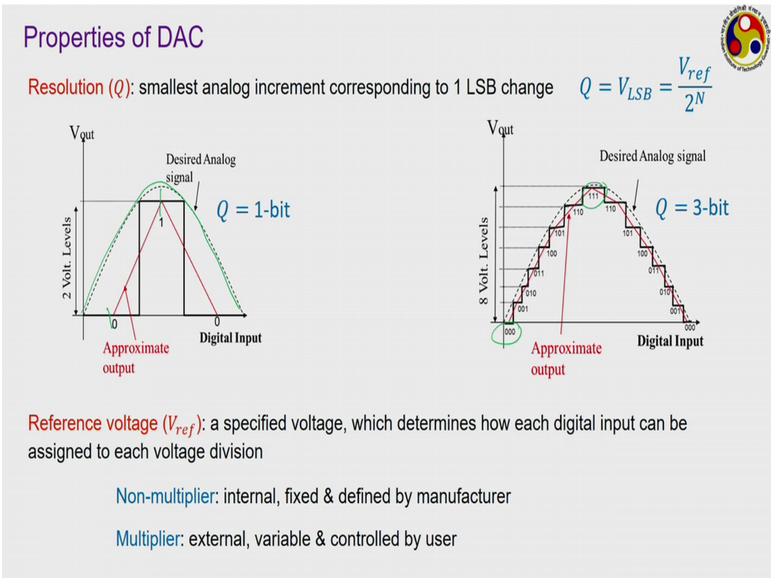
And therefore, it is giving a representation just like this either 0 at 1 position or one at the other position and all values are represented other way this whereas, the same thing if we represent by a 3 bit converter.

(Refer Slide Time: 18:27)



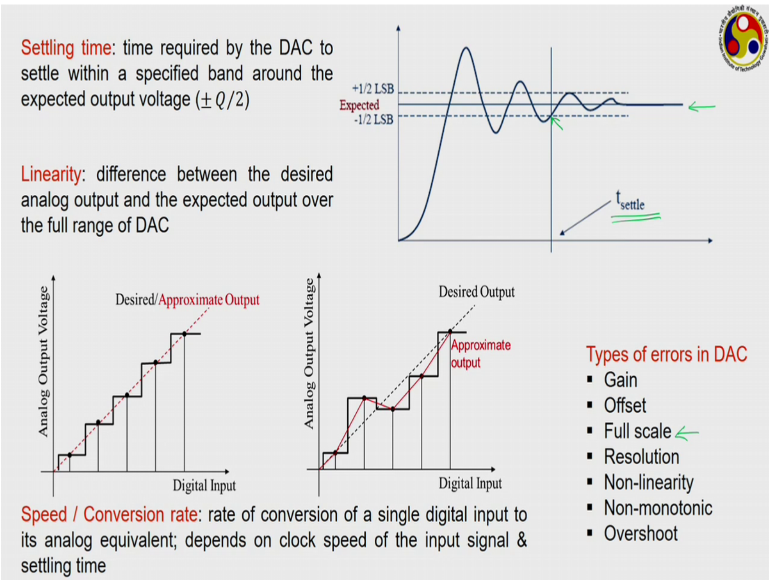
2 bit means we can have 2 to the power 3 that is total 8 number of levels starting from 0 to 7 or if we write in binary format, we can have 000 to up to 111 and so many levels we have available with us accordingly it can give you much better representation just like this. So, is 000 is the lowest position 1 1 1 is the highest position and in between we are still having 6 more levels. So, it is a much better representation that you are going to get. So, it is always better to go for a high resolution convertible there are practical problems as well.

(Refer Slide Time: 19:03)



Then the reference voltage; the reference voltage which we have already used for calculating the resolution; it itself is a term of importance because it is a specified voltage which determines the magnitude of the resolution itself. It is determines how much? Each how much voltage you are going to assign to each digital level. So, higher the value of reference definitely higher will be the resolution. And reference voltage can be of 2 types; one can be done non multiplier type which are internal to the device set by the manufacturer itself when user is not able to change it, other is a multiplier type where the user can set the reference voltage by using some external voltage source. And therefore, it can be made to be variable which is not possible in non multiplier type.

(Refer Slide Time: 19:51)



Another property of important is the settling time settling time refers to the time required by the converter to settled within a specified band around the actual output and this band we thought the band generally is equal to the resolution itself. And therefore, the band can be specified something like plus minus Q by 2 just like this. Here this one this line represents the expected output; however, during depending on the way your convert is working, we are getting a curvilinear representation where initially there is a large overshoot and then that gradually decreases to get settled within this band. So, we can allow a maximum of plus minus Q by 2 amount of error and once this term gets settled like if you look say this is a point after that the a value output value is always using that plus minus Q by 2 range and so, this is what we refer to as the settling time.

So, to note the reading or output value from your converter, we must be aware about the settling time because that is a minimum amount of time we have to provide to your our instrument before finalizing or before noting the final reading. Next property of importance is a linearity like any stamp measuring instrument. We always expect a linear behavior that is with the whatever change in the input is taking place proportion proportionate amount of change in output should also take place.

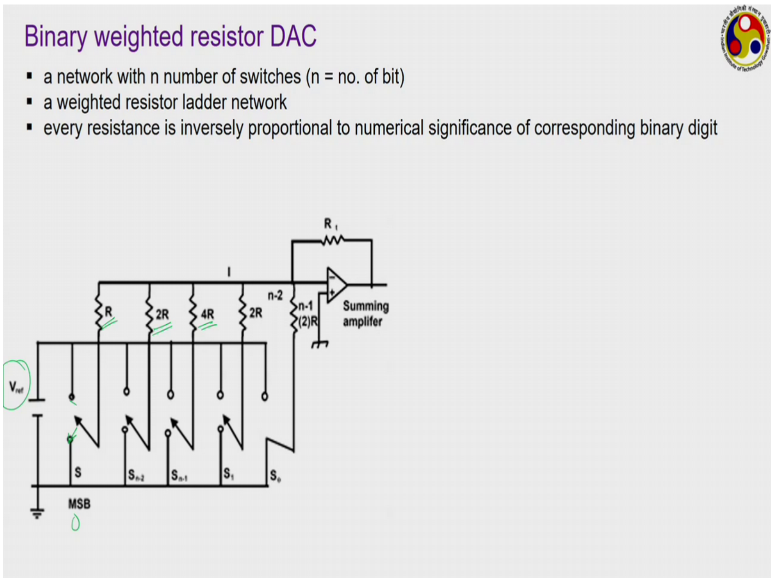
So, linearity refers to the difference between the desired analogue output and the expected output over the full range. Like see this is the case. This is the most ideal scenario as the input is changing continuously corresponding, output is also changing and the midpoints of all this intervals can be joined by a straight line. This is the desirable scenario, but this is what we make it in practice like there can be quite random variation so, non-linear representation of this output. This can lead to severe amount of error in the final reading and the speed or conversion rate is always of importance which refers to the rate at which the digital input gets converted to the analogue output.

It depends on the clock of the input signal itself and also the settling time. Like larger the settling time definitely, it will be able to give you reading within a lesser period of time, but again that affects the accuracy. So, each of them needs to be considered while designing an DAC. And still by we can have several kinds of errors like we can have errors is it a gain of the instrument. Gain refers to like the gain error refers to the change in the ratio of output to input with time whereas, offset refers to if there is a fixed amount of distance maintained between the expected output and the actual output over a long period of time. When this gain and offset comes together, then we get the full scale. I am not going to the detail of this because this terms already you know in the very first week itself; we have discussed about this kinds of errors.

The gain refer the gain error or corresponding slope related error, we have discussed in detail you know how to calculate that for an engineering student also. It is just the same thing, but it is digital to analogue conversion version that. Resolution we have already seen how resolution can give erroneous results nonlinearity. The example again, we can see here itself the example of nonlinearity error. Non monotonic is somewhat similar to this non-linearity and overshoot this is what we refer to as the overshoot the. This is your derived level, but over this entire span the output is greater than the actual input or actual expected output I should say. So, this is what we refers the overshoot. So, large overshoot can severely hamper the working principle of the instrument and even cause permanent damage to that one also.

So, these are certain properties which are of interest related to the digital to analogue conversion. There are quite a few kinds of converters, but here we shall be discussing only 2 of them which are the most popular one and also the most important ones.

(Refer Slide Time: 24:09)

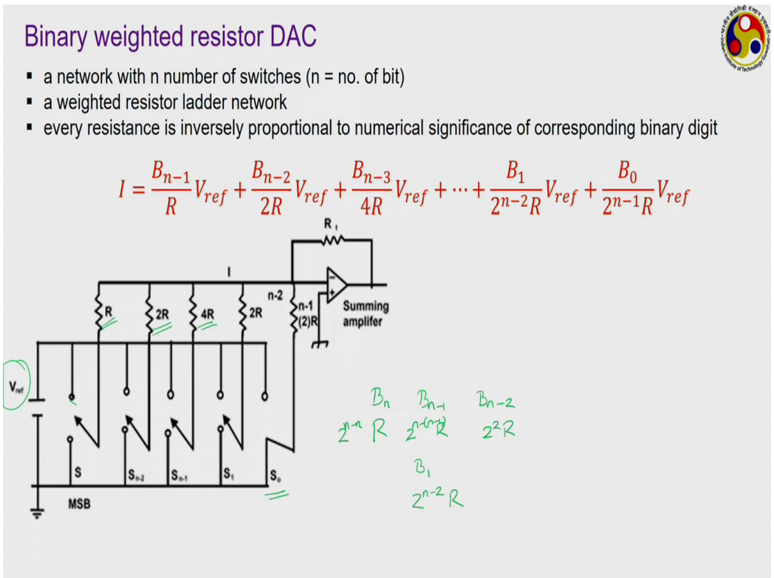


The first one is called the binary weighted resistor. In case of a binary weighted resistor, we have a series of resistors each connected to 1 bit of the binary input; that means, if there are have you are having n number of binary sorry if you are instrument is of n bits, then we are also going to have n number of resistors.

But this resistors are not equal rather they follow a particular pattern. Like the resistor connected to the most significant bit; if the value of that one is R then that one connected to the next one each value will be double of that is 2 R. The next one will be having a value of 4 R and this way it will keep on going. So, we have a network of n number of switches. The switches are controlled by the binary input of the corresponding bit like say for the most significant bit when your most significant bit is equal to 1, then the switch is closed or the switch connects this particular portion. So, it is in contact with the voltage source.

However when your most significant bit goes to 0, then the switch contacts this grounded portion. So, no current flow through this, then the weighted resistor of ladder network that we have here every resistance is inversely proportional to the numerical significance of corresponding binary digit; just what I mentioned like for the most significant bit it is R, then it keeps on becoming double of the immediately neighboring one as we keep on going across the bits. Then what will be the resistor corresponding to the least significant bit, then the first one is R.

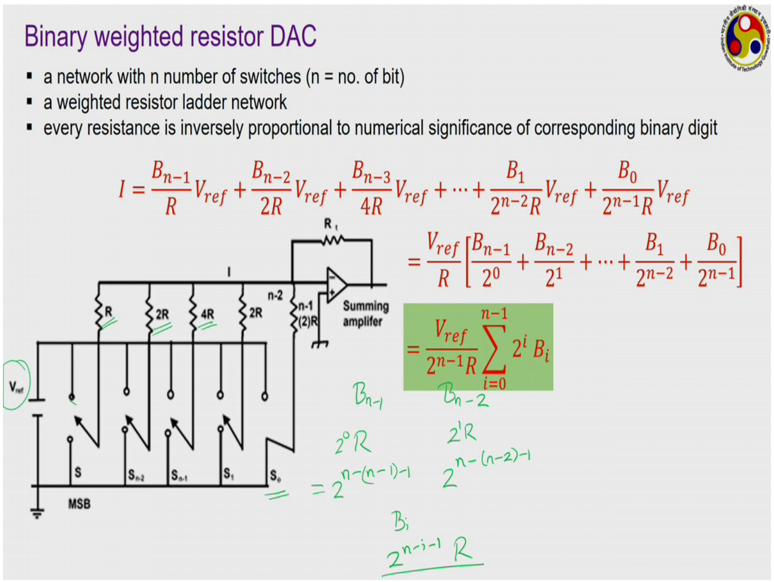
(Refer Slide Time: 25:47)



The next one first one which is associated with B n position is R then the one associated with B n minus one position is 2 R. So, we can write this to be 2 to the power 0 R this to be 2 to the power one R then the one associated B n minus 2 position is 2 square R. So, this way keep on keep on going the one associated with B 1 position. What should be the value of this? Let us see quickly the, it should be 2 to the power n minus 2 into R; if we keep on following this pattern because instead of writing this to be 2 to the power 0 we can write this to be 2 to the power n minus n. Similarly we can write this to be 2 to the power n minus n minus 1 and the same we are writing for all of them and the final one.

So, this way we can keep on writing the resistors for all of them. This is what we have here. So, the total current that will be flowing through this entire circuit should depend on the reference voltage divided by corresponding R and the value of the switches. This B value is refers to the value of the bit if the bit is 1, then this you will be getting current as V ref by R where as B 0, there will be no current flowing through this and same for each of the resistor.

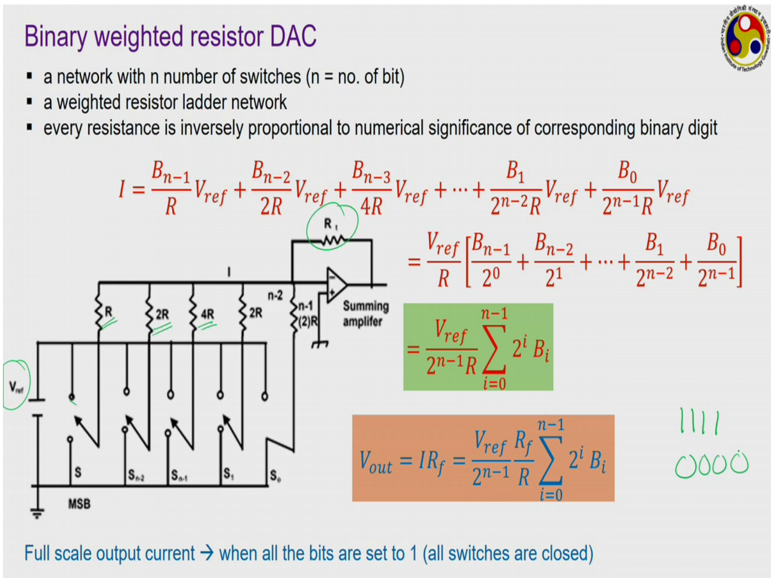
(Refer Slide Time: 27:13)



So, we sum them up starting from B n minus 1 going to B naught actually I made a mistake while writing this. So, the most significant bit we refer as B n minus 1 corresponding resistor is R or 2 to the power 0 R, then we can write this to be 2 to the power n minus n minus 1 plus 1 something like this or rather minus 1 just to make it 0.

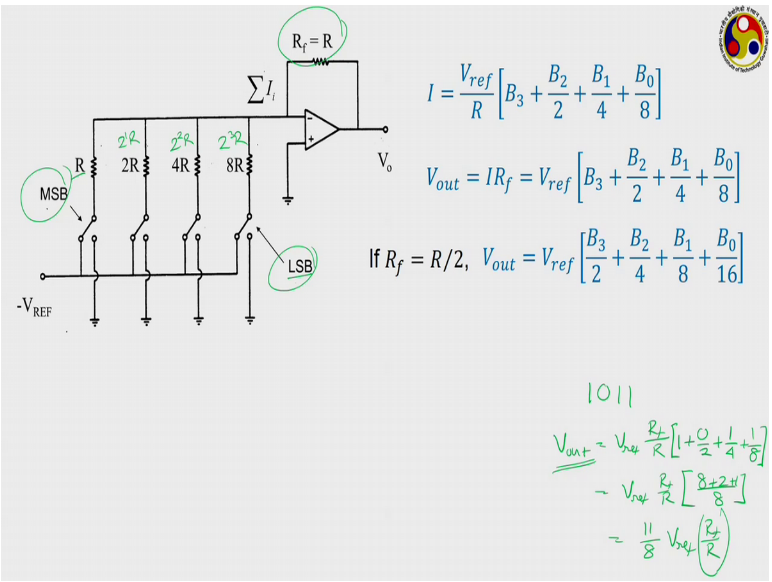
Then the 1 in the next digit bit 2 to the power n B n minus 2, its value is 2 to the power 1 R; then we can write this to be 2 to the power n minus its position n minus 2 R minus 1. So, the 1 in the ith position, then what we should write? The corresponding resistor should be should be 2 to the power n minus i minus 1 into R. This should be the corresponding resistor. This is exactly what we have written here and each of them is having corresponding resistance the magnitude of resistance keeps on changing as we move from most significant bit to the least significant bit. The one connected to the least significant bit is the highest resistor, then this is the total current then how much will be the voltage and the output? There should be this current multiplied this R f.

(Refer Slide Time: 28:35)



So, it is I into R f and we have the expression for this let us. So, the full scale output current will be possible when your all the bits are having one like if you are dealing with a 4 bit resistor or rather 4 bit converter, then if all of them are one then you will be going to get the maximum current which you refer as the full scale. Similarly when all are 0, then no current will be flowing through this output voltage also will be equal to 0.

(Refer Slide Time: 29:05)



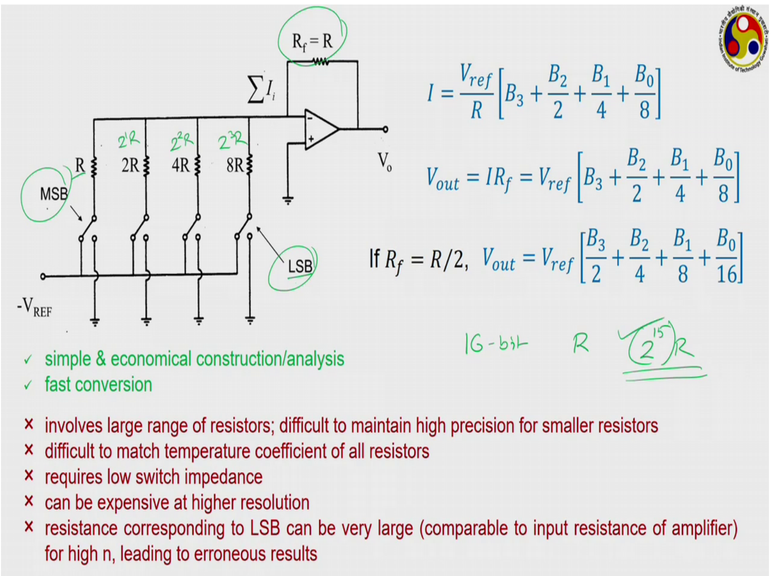
Let us take the example of this particular resistor. In this particular resistor we are dealing with a 4 bit converter. So, 4 bit means first one you have a resistor R, second one is having 2 R or you can say 2 to the power 1 R, then next one is 2 square R and third one is 2 cube R which is connected to the least significant bit this one.

V ref amount of voltage has been applied and R f this resistor taken to be equal to R. Then what is the current that is flowing through this? It is very easy you can calculate to be V ref by R into B three as we have taken R outside. So, B 3 plus B 2 upon 2 plus B 1 upon R B 1 upon 4 plus B naught upon 8 where B naught refers to the least significant bit, B 3 refers to the most significant bit and then output voltage will be R f times of this and as R f is equal to R we get this.

So, therefore, say we are dealing with a situation where your binary input is 1 0 1 1, then how much will be your output voltage? Your output voltage will be equal to V ref into R f upon R into one correspond to B 3 plus 0 corresponding to B 2 plus 1 corresponding to B 1 plus 1 corresponding to B naught that is V ref into R f upon R and then if we add all of them together we have 8 plus 2 plus 1 that is 11 by 8 V ref into R f upon r.

So, this down, by changing the value of this V ref R f and R or I should say the ratio of this R f upon R and also the magnitude of V ref we can get any desired level of this V out. This situation where R f is equal to R by 2 we get this value. So, by just modifying the value of R f by R ratio and the value of this reference voltage we can produce any level of output voltage corresponding to a given digital one.

(Refer Slide Time: 31:21)



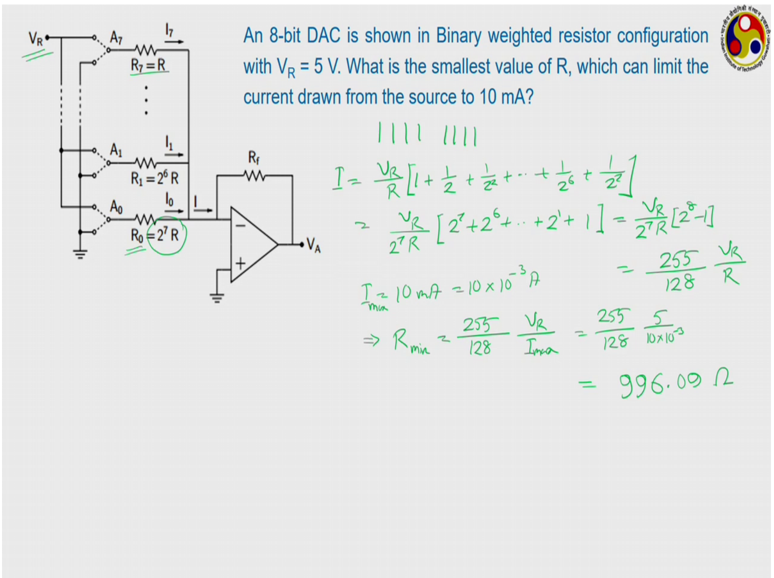
So, the biggest advantage of the structure is it is a very simple easy to understand structure it is an economical construction from design point of view and also easy to analyze and quite fast conversion. Because all of them are working parallel, so, it is very fast, but it involves a large number of resistors.

Particularly when we are dealing with a high higher bit one then quite difficult to maintain the precision and accuracy level and the also the stability of the lower resistors, like suppose if you are dealing with a 16 bit converter, then if the one associated with the most significant bit is R the one associated with the least significant bit is 2 to the power 15 times of this R which is an humongous value, even if your R is small this one is extremely large resistance that you are talking about.

So, it is quite because quite difficult to handle with them, another problem happens actually all these problems associated with the presence of so many number of resistors. Now if you are doing or dealing with an application which is associated with substantial change in its temperature, then it will be very difficult to match the temperature coefficient of all this resistors. Because you know that resistance of a resistor changes with temperature and it will be very difficult to get so many resistors with identical value of the temperature coefficient of resistivity. And therefore, they may lead to erroneous results, particularly at higher temperatures then we required low switch impedance can be expensive at higher resolution just because of the precision related issue with lower resistor.

And also when you are dealing with a resistance very large resistance corresponding to LSB, like just the situation you are talking about. There this resistance itself may be somewhat similar to may even larger than the input resistance of the amplifier itself. And therefore, that will lead to significant amount of error in the final result. So, as long as you are dealing with low number of bits then it is fine, it is an excellent the kind of converter, it is a quite accurate, give very fast conversion. However, as the number of bits keeps on increasing it becomes quite difficult to handle.

(Refer Slide Time: 33:37)



Let us solve one problem on this, here we are our problem corresponds to an 8-bit DAC here just shown here, this is the least significant bit having resistor R naught it is the most significant one having resistor R.

So, it is R, next one is having 2 R this way the least significant bit is having 2 to the power seven times of R. Here it is given that this V R the reference voltage is equal to 5 volt, then what is the smallest value of R that we can allow which will provide you, which can limit the current drawn from the source to 10 milli ampere. This is a fabrication related problem that is it is said to the manufacturer that we have to limit the current to 10 milliampere, the maximum current that may appear in the system.

And so accordingly he has to choose the value of this resistors. Now how can we proceed? The maximum value of the resistor, how can I select this? This is an 8-bit DAC. So, what is the maximum binary input that it can have? The maximum will be the one when all the 8-bits are having 1 in it. So, this is the largest possible input that it can have.

So, how much is the current corresponding to this, the current corresponding to this will be V R divided by R into 1 plus 1 by 2 plus 1 by 2 square plus dot plus 1 by 2 to the power 6 plus 1 by 2 to the power 7 where R by 2, 2 2 to the power 7 R is the resistor for this least significant bit. Or if we take just for ease of calculation if we take 2 to the power 7 out of this then we have 2 to the power 7 plus 2 to the power 6 plus 2 and 2 to the power 0, that is 1 here.

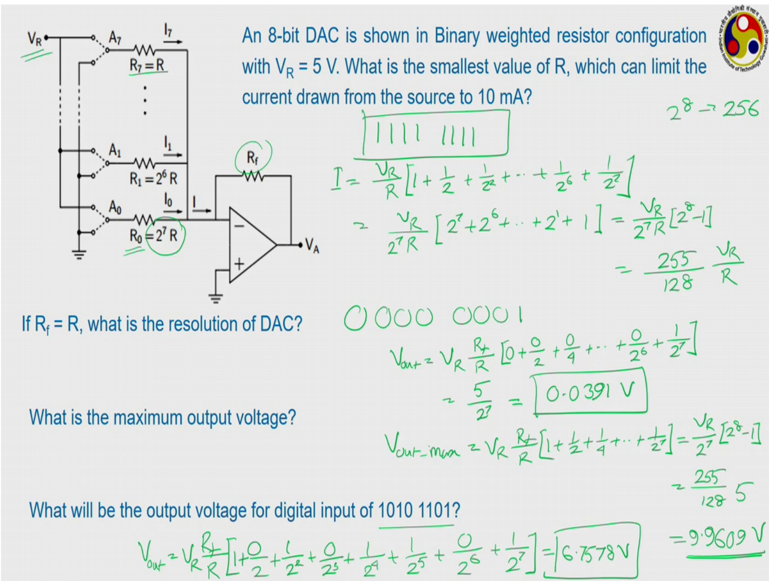
So, how much should be the value of this? This is just like a geometric progression is not it where the starting value of the smallest value is 1 and they are having a ratio of 2, the neighbouring values. So, if we calculate properly then this comes V R by 2 to the power seven R and this entire thing will be coming to the 2 to the power 8 minus 1 by 2 minus 1 so like this.

And so we have to 2 to the power 8 is 256 minus 1. So, it is 255 by 2 to the power 7 is 128 into V R by R. So, that is the expression covered for the current, when all the bits are switched on. Now in this problem it is given that this I is equal to 10 milliampere in the extreme situation, that is 10 into 10 to the power minus 3 ampere. So, if we rewrite this expression then the R the smallest value of R R min I should say this was I max. So, R min should be 255 by 128 into V R divided by I max. So, we put the numbers here 255 by 128 into here V R is given as 5 volt and I max is given as 10 into 10 to the power minus 3.

So, we have to calculate the value and I actually have pre calculated the number. So, it is coming as 996.09 ohm. So, this is the smallest value of resistance that we can put in, practically you have to always like to put in resistance value higher than this. So, this way we can do calculations about the design parameters, how to decide the value of resistor or even how to decide the value of the voltage. Let us extend this problem a bit, next problem is if R f is equal to R what is the resolution of this DAC? We this particular R f is given to be equal to R, now we have to calculate the resolution of this DAC.

How can we calculate the resolution, what the resolution refers to? The resolution refers to the change in the final output with the smallest possible change in the input. Now what can be the smallest possible change? Think about what is the smallest possible input or so there rather I should say what is the smallest value of output you can get that is 0.

(Refer Slide Time: 38:21)



And it should corresponds to which input? It should correspond to the input of all 0's. So, this is going to give you an output of 0 volt. Now if we change this by the smallest possible amount that is change by 1, then how much is the change that your going, that is going to take place that should be your resolution.

So, let us calculate the output voltage corresponding to this, your output voltage in that case will be equal to V R into R f upon R into all this resistance now here all are 0 only one that is appearing, if you expand 0 0 by 2 0 by 4 this way it continuous 0 by 2 to the power 6 plus only one appearing is the least significant bit. So, R f is R; that means, you are value that is available with you is equal to V R is 5 divided by 2 to the power 7, actually I lost where I wrote down the value. So, it is coming to be 0391 volt.

So, this is the resolution; that means, each of the division it is 8-bit DAC. So, 8-bit means total 256 levels it can have and each of the level corresponds to a voltage difference of 0.0391 volt; which is a sufficiently small resolution and of as 8 bit suggest it is a quite good converter. If you can extend this problem to identify the maximum output voltage that can that we can have.

Now, when we can have the maximum output voltage? Minimum output voltage is all inputs are 1, then sorry all inputs are 0. So, we shall be getting 0 output voltage, then maximum output voltage you are going to get when all inputs are one just like this. So, what will be the value of the corresponding output voltage? We actually know the value of the R y now, but the value of R is not required, the maximum output voltage which is the maximum that you want to calculate when all of them are set to one. So, that will be equal to V R into R f by R into all set to 1 1 plus 1 by 2 plus 1 by 4 plus 1 by 2 to the power 7.

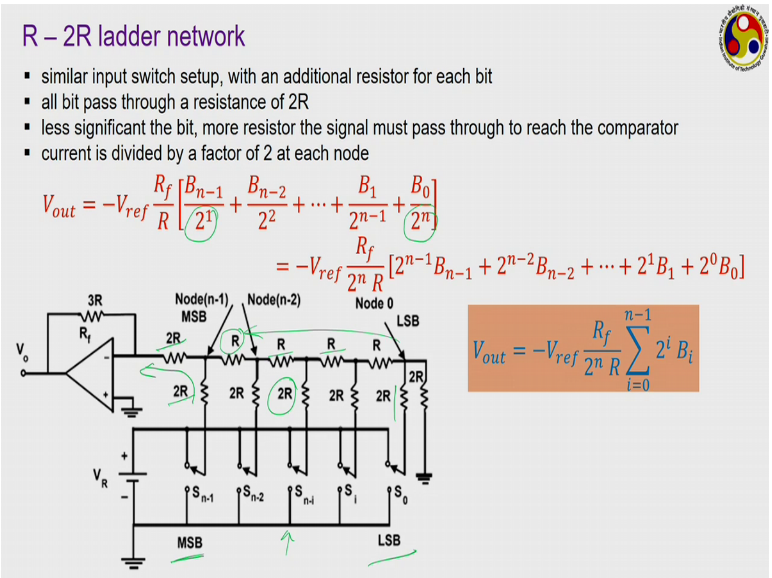
So, again if we calculate following the same way and putting R f equal to R, then we are going to get this to be V R divided by 2 to the power 7 into inside this bracket it is 2 to the power 8 minus 1 that is 255 by 128 into V R and we know the value of V R is equal to 5 volt. So, 255 by 128 into 5 that gives us 9.9609 volt this is the maximum output voltage that will correspond to when all inputs are set to 1. I have one final calculation here, what will be the output voltage for digital input of this particular one? Now the following the same way you can calculate, let us just calculate following the same pattern, here your output voltage will be again V R into R f by R into let us put the resistor.

So, first bit be for the most significant bit this is equal to 1, then it is 0 by 2 then it is 1 by 2 square then gain 0 by 2 cube plus 1 by 2 to the power 4 plus 1 by 2 to the power 5 0 by 2 to the power 6 plus 1 by 2 to the power 7 and once you put all these numbers then you are going to get 6.7578 volt as the final answer.

So, corresponding to any digital input within this 8 bit range you can calculate the output voltage, just following this sample calculation. So, this is a quite good example about how to deal with a binary weighted resistor network or ladder network for conversion of a digital input to corresponding binary output.

I hope you understood this, similar problems will be given in the assignments also and I am sure you will be able to solve it, but let us quickly check the other kind of converter that we can have, as you have mentioned there are so many number of resistors available here. So, it quite often may become difficult to deal with particular as been here been large bit or we are trying to get about a high resolution converter like this the in this particular example corresponds to 8-bit and that is more or less the practical limit of operation for such resistors, we hardly you will find a binary weight resistor of using of 10 or 12 bit.

(Refer Slide Time: 43:43)

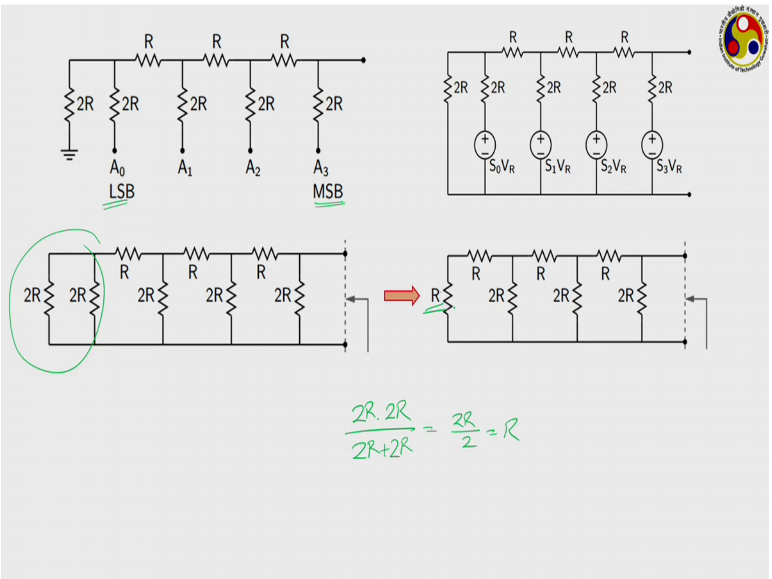


So, the next one that we have is called R-2R ladder network. So, in this case here each of your bits here your switching setup is quite similar, but we have an additional resistor for each bit. Like if you see each of these bits, this is the most significant bit this is connected with the resistor of 2R. So, all bit passed to this resistance of 2 R and then in between these 2 connection there is this resistor R, this additional resistor.

Similarly, if you focus to any one of the, like if you check out this particular bit this is a resistor 2 R and either side of this connection you have this R resistor. So, the least significant the bit more resistor the single has to pass through. Because like when we are talking about the most significant bit it will only while going through the comparator it will only goes through this, means it encounters only this resistance, this 2R and another 2R. Whereas, if you come to the least significant bit that will pass through this 2 R and then this entire series of R networks or R resistor it has to pass through.

So, the lower the significance of the bit more number of resistor the signal has to pass through to reach the comparator, here current is divided by factor of 2 at each node following the Thevenin’s theorem, accordingly we get this particular expression of the voltage output which we can combine. Here this in like in the previous case of binary weighted resistor here we had B n minus 1 by 2 to the power 0 and this one was 2 to the power n minus 1. However, there is an additional 2 factor is coming in the denominator here, I am giving this is the final expression where we have an additional 2 in the denominator; but how we got this expression? Probably it will be easier if we discuss it as smaller example.

(Refer Slide Time: 45:29)

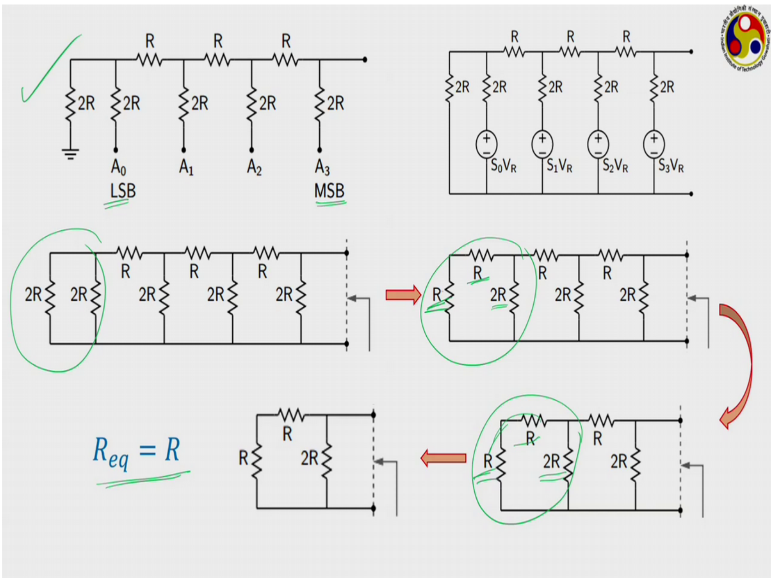


Let us take this circuit where we have just 4 bits, this is a most significant one, this is the least significant one. So, we have to keep on reducing the circuit to smaller case, this circuit can be thought to be equivalent to this where all this s naught S 1 S 2 and S 3 refers to the refers to the value of the concerned bit like S naught refers to the value 0 or 1 which occupies the least significant bit.

Similarly S 3 correspond to the most significant one and we have to we can reduce this circuit to a much lesser one to calculate the final output resistance value. Like if you think about this way all the inputs are 0, let us say all this s values are 0 then this is perfectly grounded each of them.

Let us take first this portion, there you can clearly see there are 2 values of 2 R resistors in parallel; then what is the corresponding equivalent resistor? Corresponding equivalent resistor will be R only because you know their equivalent resistance, sorry the equivalence of this 2 R resistor will be 2 R into 2 R divided by 2 R plus 2 R. So, that leaves you 2 R divided by 2 that is equal to R. So, this is this R that we are getting, this is following Thevenin's theorem we can reduce it further.

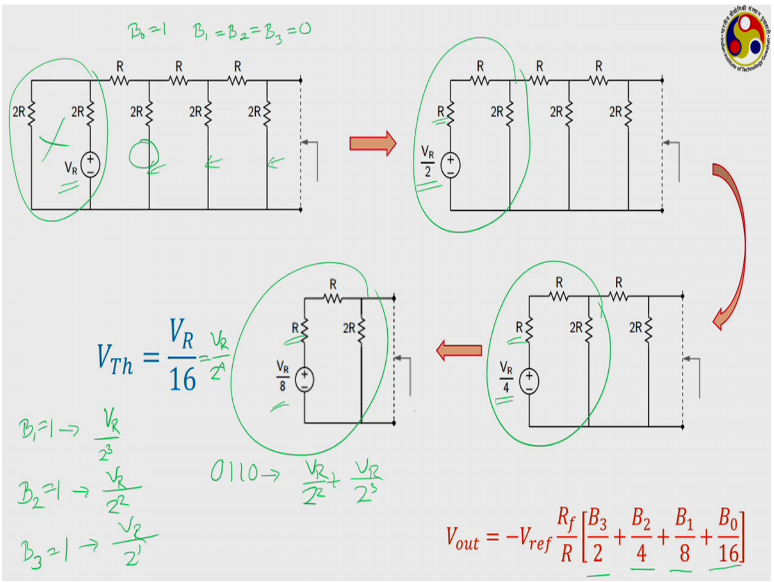
(Refer Slide Time: 46:57)



So, if we now think about this particular block, this block what we have we have one R here another R here 2 R resistor in series and another 2 R resistor in parallel. So, if you reduce this, this again will reduce to another R resistor like this.

Now, we take this part, again we have one R another R resistor in series. So, the net of this 2 is 2 R and that is another 2 R in parallel. So, combining them we get R; finally, what is the equivalent resistance of this? So, R plus R in series 2 R parallel to this is 2 R. So, another R we have this entire circuit comes to be or comes to have an equivalent resistance of R only, this is the biggest advantage of this R 2 R ladder network. Means whatever may be the number of bits that you are dealing with the output resistance is always equal to R, we are using just 2 resistor levels R and 2 R and their oriented such that their combination gives you a net output voltage of sorry net output resistance only of R.

(Refer Slide Time: 47:57)



Let us take the example an example where your s naught or B naught, now let us take to a notation of B naught. So, your B naught is equal to 1 all other ways that is B 1 B 2 and B 3, they all are set to 0. So, the situation is somewhat like this, this all are grounded and, but this one is having this V R there reference resistor. This can be now we can reduce this, say it take this particular portion there are 2 2R resistors.

See if we combine them their equivalent becomes R and this voltage get divided by V R by 2 now we take this particular circuit, we reduce that the voltage becomes V R by 4 and the equivalent resistance is R, now we take this particular circuit this is just simple application of the Thevinen's theorem and circuit theory.

So, again it becomes V R by 8 in each step the voltage gets divided by 2 by a factor of 2, whenever we are moving from one to the next one the voltage keeps getting divided by factor of 2 and in all cases our equivalent resistance is coming to be R, like here also the voltage is V R by 8 resistor is R.

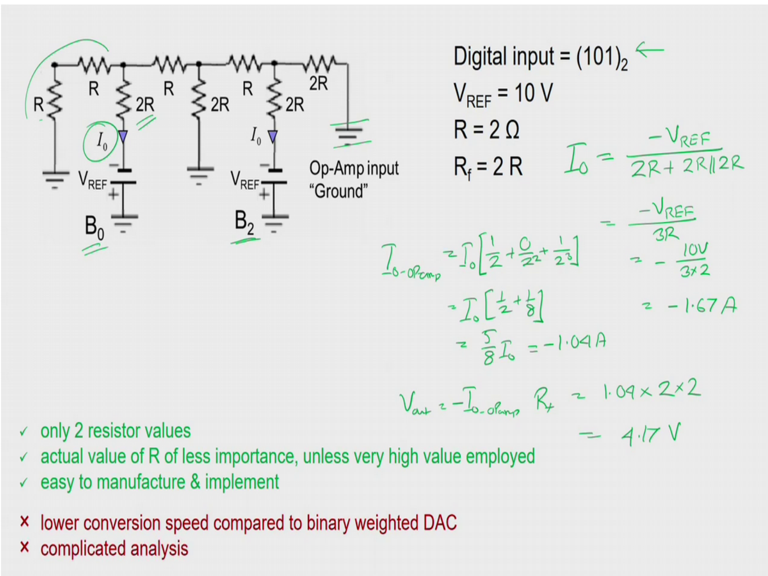
Now this is only circuit that is left with us. So, again the equivalent resistor will become R and the voltage will become V R by 16. So, corresponding Thevenin voltage we are getting as V R by 16; that means, when you are dealing with an input of 0001 it is like this or instead of writing this. So, you can think about the anyone appearing the least significant bit will contribute V R by 16 amount of voltage.

Similarly, if we set say d one equal to one and else everything else to be 0, then this circuit does not come into picture and actually you are we having this V R voltage appearing here. So, if we calculate that its contribution will be, it is per like here it pass through the voltage pass through four nodes. So, we got V R by 2 to the power 4 or we write it as V R by 2 to the power 4, but here it will be here by 2 cube.

Similarly when we have when we have B 2 equal to 1 and others are set to 0 then that will contribute V R by 2 square and when the most significant bit is set to 1 everything else to 0 then that will contribute V R by 2 to the power 1; that means, that way we can calculate the voltage contributed by each of the bits.

And now depending on which of the bits are available and which are not we can always keep on adding them or subtracting or sorry we can always keep on adding them to get the final output voltage. So, like when we have an input say 0110, then what will be our voltage? Then the most significant bit is not there, the next one is 1. So, the bitwise 1; so, it will contribute V R by 2 square B three is one that will contribute V R by 2 cube least significant is 0 so that will not contribute anything-. This way we can get the final output voltage and this is the expression. So, B 3 contributes B 3 by 2 our B 2 contributes B 2 by 4 B 1 by 8 and least significant contributes B naught by 16. And now multiplying with the R f we get the final output voltage from this.

(Refer Slide Time: 51:29)



This is an example of dealing with here we are dealing with talking about a 2 bit resistor, this is the least significant bit this is the most significant bit and your input current digital input is 1 o 1 that is the most both most significant and least significant bits are set to 1 and a intermediate one is 0 the reference voltage is 10 volt here R is given to be 2 ohm and R f is said to be 2 R. Then how can we calculate the value of this current first.

So we have to calculate the final output voltage, let us calculate the output current first your I naught the current will be equal to minus of this V ref divided by the equivalent resistance, How much is the equivalent resistance? We have this 2 R associated with this in series and this 2 R this 2 R is in parallel to that. So, 2 R parallel 2 R so; that means, we have minus V ref divided by 3 R.

Now V ref is set to be 10 volt divided by 3 into 2 this 6. So, minus 1.67 milliampere or I should say may not milliampere 1.67 ampere. So, how much is the current that is coming to this opamp that current I naught reaching the opamp then can be written as this I naught into the contribution coming from the most significant bit is 1 by 2 from the next 1 is 0 by 2 or sorry 0 by 2 square and from the least significant bit is 1 by 2 cube, that is I naught into half plus 1 by 8.

So, 5 by 8 times the I naught. So, 5 by 8 times 1.67 minus 1.04 ampere then final output voltage will be I naught of this opamp into R f that is 1.04 minus of that, into R f is how much? 2 R into 2. So, that is something like 4.17 volt. So, this way we can calculate the output voltage that you are getting from this resistor network, it is a much more complicated structure compared to the binary weighted resistor circuit that we have discussed.

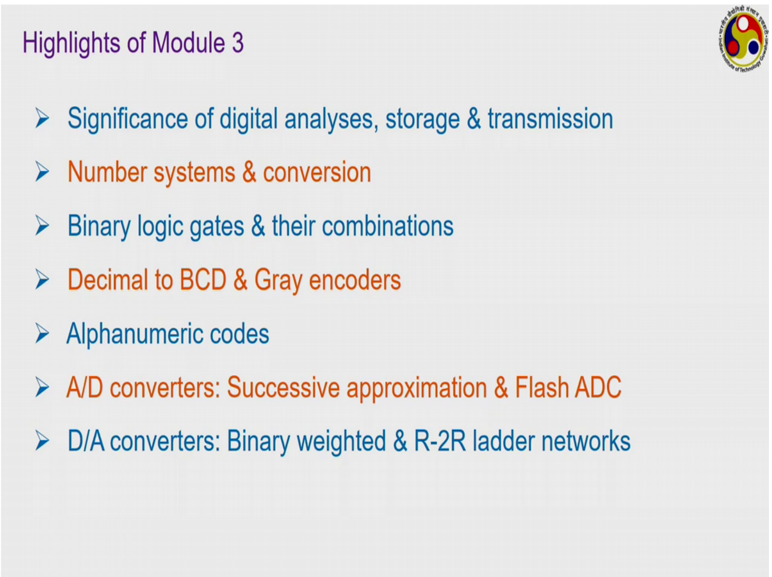
But it has much bigger advantages once you have control over. This the biggest advantage is there are only 2 resistor values to consider R and 2 R. Whereas, in case of the binary weighted resistor we have to consider a very large range of resistance to deal with.

Actual value of R is of less importance unless very high values are employed here, easy to manufacture and implement; however, its much smaller speed compared to the binary weighted value which is having some kind of parallel processing and so, very quick to give the final output and much complicated to analyze this particular system.

You need to have proper idea about circuit theory to do this, but still because of such simplified final representation only and if requirement of only 2 resistance values. So, this is probably more popular one when you are looking for very precise measurement and particularly when you are looking for larger bit of measurement larger resolution. However, when you are looking for somewhat restricted resolution up to 6 bit or 8 bit then the binary weighted one is more preferred, simply because of its simplicity.

That takes us to the end of our week number 3; here we have talked about the application of digital techniques in measurement.

(Refer Slide Time: 55:33)



So, we started with defining the significance of digital analysis, storage and transmission over corresponding analogue counterpart then we talked about the number systems conversion from one system to the other Particularly conversion from decimal to others and from other system to decimal and from there we established how I binary is so important compared to the other systems. Then we talked about the binary logic gates, their combination to give different kind of conversion of binary digits.

Then we talked about the decimal to BCD and gray encoders, we have talked about alphanumeric codes in detail for together ASCII character sets, the Unicode systems and also we talked about the barcodes. Then we have talked about the analogue to digital converters out of which successive approximation of flash ADCs are generally the most popular one from modern technology point of view; but sigma delta if it is quite complicated, but can be much more accurate.

And today we have discussed about this digital to analogue converters where we have discussed only 2 configurations, the binary weighted one and also the R 2 R ladder networks. So, please revise all these lectures properly if you have any query please write to me, I would request you to refer to books or maybe over internet because you will get lots of different kinds of discussions regarding each of these topics.

This course being focused more on mechanical measurement. So, (Refer Time: 56:57) details of electronics is not required, but at least the topics such as the number systems, how to combine the logic gates what are the working principles of each of these converters, if you have understood that is sufficient. So, that takes me to the end of this particular week, it was actually a quite exciting week for me because we talked about something which is quite out of scope for a mechanical engineer.

But being as we are living in a digital world I felt it is extremely important to have some idea about how to convert a normal analogue input to digital and how to get it back to the analogue form and that is why we have discussed in detail in this week.

I hope you have enjoyed it, please do the assignments again and I repeat if you have any query please write to us immediately. So, I will try to be shouting that out as soon as possible. So, next week we shall be talking about the processing of the outputs. So, till then bye, I am signing off for this week. So, take care.