Mathematical Aspects of Biomedical Electronic System Design

Professor Chandramani Singh

Department of Electronic Systems Engineering

Indian Institute of Science, Bangalore

Week – 11

Random Variables and Signal Conditioning Circuits

Lecture – 35

Introduction to signal Conditioning circuits for biomedical devices

Hello all. Welcome to the module. This course is on Mathematical Modeling of Biomedical Systems and Biomedical Devices Design. Till now you have thought how mathematical modeling can be done for different types of biomedical tissues and systems and their underlying principle. How these principles can be used to analyze the signals that you get from the biomedical devices. In reality how do we get these signals? How do we interface those signals to electronic systems for further analysis? So, these are some of the questions that we always have to think when we are designing a complete system.

So, if you look into any device or the system, it consists of input and output. It need not to be only for the system or a device, it can be any subsystem of a system to where any system if you can divide into multiple subsystems, each subsystem will have its own functionality combining together it will form a complete system. No matter what whether it is a individual system or whether it is a subsystem, it will always have inputs as well as an output.

So, what is an input here? An input is what we are trying to measure or what we are trying to analyze. Whereas, an output it gives with the information about the input in order to communicate to the next corresponding system or if it is an end user, the output whatever the system is providing will be relevant to the input and where the end user can understand it. But in order to do all these things, the input system should have ability to understand what is the parameter that is going to be measured in the real world.

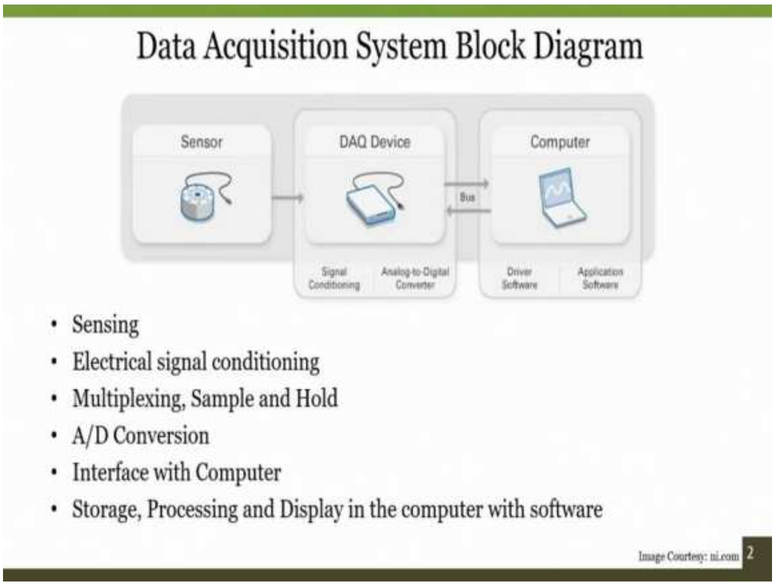
For example, say when we are dealing with this biomedical systems. So, when I say a system, electronic system, which means that this complete system uses an electronic component, whereas a bio-related, biomedical related input is nothing but in the form of different physiological principles. It generally will not be in the form of where electronic circuit can understand so the first subsystem when you look into these electronic system designs would be transducer.

Let me give you a brief idea about the difference between a sensor and transducer. You might have already heard about a sensor. You might have also seen. People will intermittently change the word as a sensor or transducer both way they consider it as same. But there is small difference between a sensor and the actuator, sensor and the transducer and the actuator and the transducer too.

In reality the transducer is a device which converts any form of energy into – one form of energy into any form of energy. One form to the another conversion if it can do it is called a transducer. Whereas a sensor, which converts one form of energy into an electrical output where as an actuator is nothing but an electrical output – electrical input will be converted to a mechanical action. So, that is why when you look into actual terms of the sensor and the actuator a sensor has generally been mentioned it as an input transducer whereas, an actuator is an output transducer.

But why do we have to discuss about this? Whenever we are trying to analyze the signal that is being acquired by an electronic system, the parameter or the input measurand always will not be in the form of where the system is capable to understand it. So, in order to have a bridge between the actual physical measurand to the electronic system unit, we always have to use some kind of a sensor that converts the input measurand into an electronic electrical signals where the next part of the electronic circuit design, electronic circuit systems can understand it.

(Refer Slide Time: 05:15)



So, in today's session what we are going to see is that as in the previous sessions we have already discussed about how do we model mathematical model different biomedical tissues and the system and their underlying principles. How do we get the signals? How do we interface those signals to electronic systems for further analysis? What is the need of signal conditioning circuit? So, all these parameters, all these topics we will be discussing in today's session.

So, as I told you, as I briefly explained to you about a complete system point of view, in general you will always have a sensor that converts your input physical parameter, physical measurand into n electronic system understandable signals. So, even in this case if your input is, your biomedical signal, the output will be in the form of electrical output voltage. So, you have input as well as an output and that will be connected to a signal conditioning circuit followed by ADC.

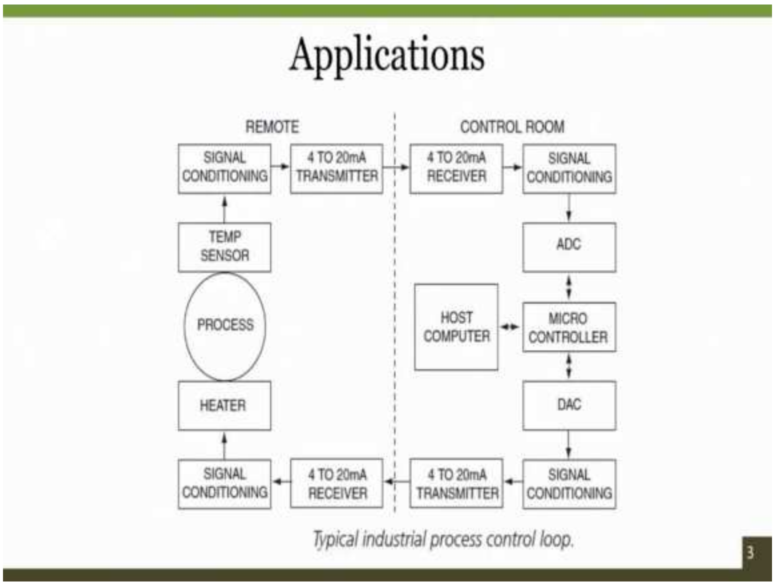
So, the idea of this ADC is in this digital world if you want to interface or if you want to communicate faster or if you want to store the data, analog signals consume lot of energy, lot of resources and everything. So, the one easiest way to do everything in a small robust environment is by using microcontrollers or digital platform. But whereas, the real world signals will be always in the form of an analog in order to do that processing, we should have to convert analog to digital conversion.

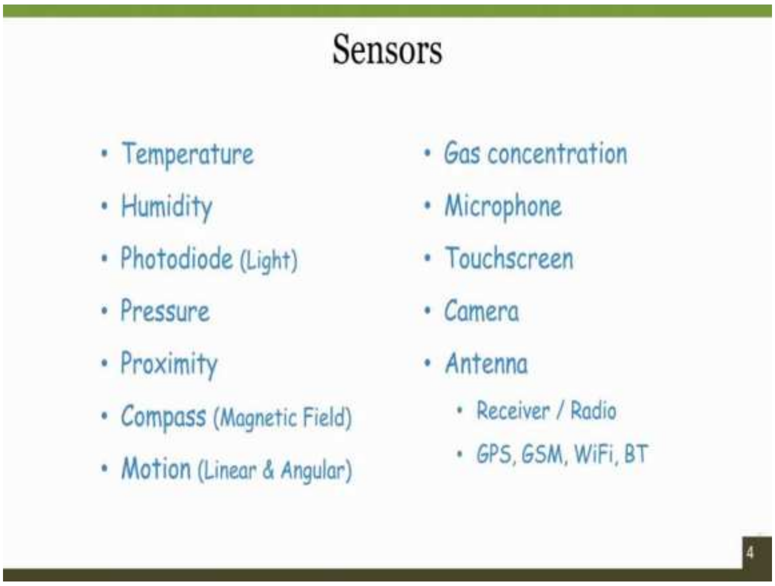
But again, if I consider it as a subsystem where the output from the sensor is nothing but an input to the signal conditioning circuit and output of the signal conditioning circuit is an input to the analog to digital converter, you may ask a question why cannot we directly interface a sensor to the ADC? Of course, we can do that but we do not know whether the output of the sensor is capable to directly interface analog to digital converter.

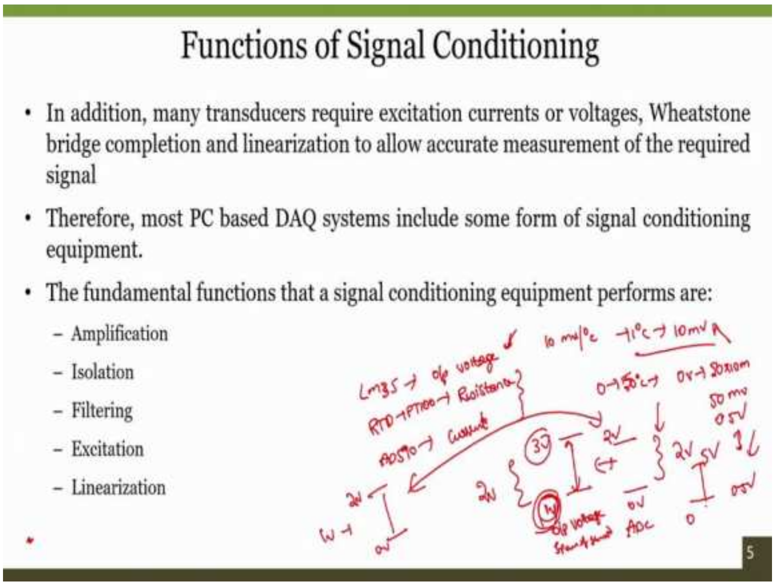
So, in case if it is not capable enough then we require to use a signal conditioning. When I say capable here, multiple factors that we have to keep in our mind when we are interfacing. One is the levels, the output level of course when I say a system output side of the sensor system, sensor device, which will be completely electronics anyway the sensor is also in the form of an electrical output voltage where this another the next level of subsystems will also deal with a complete subsystem, electrical signals where is the complexity in interface.

The complexity lies between the signal amplitude, signal isolations, and levels, matches, whether it has a very good match with respect to the input and output, so all these factors will come into effect to make us aware whether this is whether this sensor output can be directly interfaced to the next system or not. In case if it is not, we should always have to build another interfacing system or a signal conditioning circuit in order to act as a bridge between your previous system to the next system.

(Refer Slide Time: 08:52)







So, the role of – the major role of these signal conditioning circuits will be amplification, isolation, filtering, excitation as well as linearization. So, these terms you would have already heard. You may be knowing the definition but how do we do? How do we design is what we are going to see in this today's session.

Of course in the last session, you have already gone, we have already introduced you to the simulation software where once you design the system, once you design according to your input and output, how do we analyze the system performance whether it is up to our requirement or any deviation from our requirement or not. So, those simulation software will be helpful to us to further analyze the design system.

So, when I talk about most of the industrial applications, so no matter what your sensor data, if you want to directly interface to a microcontroller or a digital platform, you should have always have to follow certain intermediate steps in order to match between both the things. So in this case, in this industrial application, for example say you have to measure some temperature of certain process, it can be body temperature or it can be some other industrial application when you deal – when you see a temperature of a boiler or a unit.

So, no matter what when you look into that, when the input to be – input measurand is to be – is to measure the temperature, which is not in the form of an electrical signal, that temperature because temperature physics is completely different than the electronics that we use. So, you will always use a sensor that converts a temperature information about the temperature into electrical output voltage or a resistance change which is directly proportional to the temperature.

That change we may not, we cannot directly interface to an ADC because the output voltage for example if you take LM35, the temperature, when you look into the sensitivity factor of those sensors, it will be very, very less, somewhere in the range of 10 millivolt per degree centigrade. So, such as small voltages when we directly interface to the ADC the major problem would be the accuracy you are compromising on the complete accuracy of the system or the resolution of the system you are compromising on.

But if you are looking for a very good resolution data, very good resolution data, you require to use some kind of a bridge circuits to understand the mismatch between your input and output and create a circuit such that, that mismatch can be completely removed, compensated. So, that is nothing but your signal conditioning. But you may ask me a question what the need of 4 to 20 milliamps transmitter and the receiver is when we are interfacing to an ADC.

The reason why they use is that, in case when you are – when your sensor is somewhere remotely located to digital platform or the analyzing circuitry for example say in this case, the analyzing circuitry is your microcontroller, when we are directly transmitting the signals from the output of a signal conditioning circuits which is in the form of voltage to directly interfacing it to an ADC over a cable due to the resistance offered by your long cables, there will be a drop of voltage.

When you are having a voltage passing through resistor because when I consider each cable will have its own resistances there will be chances of; there will be voltage drop across this resistance and finally you will end up having the loss of a data. As a result, any losing information of the input is nothing but you losing the information of the input measurand.

So, in order to compensate for that rather than transmitting the information input information over long cables using a voltage if you use a current as an input since it will be in a series form, if you have a multiple resistors connected in series each resistor will be the current flowing through the complete series circuit will be the same. The loss of data will be 0, very less, negligible when I consider it.

As a result, you do not have to compromise in your accuracy or somehow you have to understand what is the loss being created by the transmission of signal over the cables and you have to somehow compensate for this transmission losses. But one simplest way is to convert the output information, output voltage which is the information about the temperature into a current form and transmit over the longer cables and again use some kind of a receiver where it again converts your current to a voltage.

So, that is nothing but your 4 to 20 milliamps of a transmitter where the signal condition circuit in this case not only amplifies your temperature input, it also converts your voltage information into a current and transmitting over a longer distance remotely then again there will be a receiver where it will understand what is the current being recorded and then use as a signal conditioning circuit that converts your input current information into a voltage that can match with respect to the input ADC levels.

If that does not match again you are compromising on the accuracy of your ADC. You are not utilizing the complete levels of an ADC, you are compromising your ADC’s capability. So then, as usual then your microcontroller, once ADC performs the conversion of your input signals to digital, then digital controller takes the lead and does the complete processing according to the requirement and in case if you have some kind of an application where based upon the input that you have analyzed, you have to actuate something.

So then, as a microcontroller again deals only with digital signals and your real world signals can all deal with a digital, you have to convert that digital to analog platform using some kind of digital to analog converters, and moreover these digital to analog converters cannot provide enough power that is required for your actual actuators.

As a result again they use some kind of a signal conditioning circuits kind of a to match the power, input power with respect to the output power and transmitting as usual as we have already discussed in the previous session why do we need a 4 to 20 milliamps of transmitter and the receiver, transmits that and according to the actuator of your system that performs signal boosting or signal conversion where heater can respond according to the input signal.

So, this is a typical application, a closed loop complete system where we will understand the input and based upon that microcontroller analyze and actuates according to the input that we receive. But when you look into the complete system, it is not so complex at the same time it is not so simple too. You have a multiple subsystem and when we are dealing with the individual subsystems the input of the subsystem should match with the previous stage as well as the output of the subsystem should match with the next stage.

So, we should always have to look about what is the input, what is the input being received and what is output that we have to give it to the next system in order to not to lose any information from the input side. So, that the actual information will not be lost, should not be lost. So, this is the whole idea of the use of a signal conditioning circuits, no matter what whether it is a biomedical signal conditioning systems or biomedical devices or biomedical systems or it is an industrial system, any system will always have to follow this logic of understanding the input as well as understanding the output part.

So, when you see there are different types of sensors. As I already discussed, most of the sensors cannot provide you the signal that can directly match with respect to the ADC. So, to understand the mismatch between both the functional of both the systems and creating proper bridge between both the functions is the role of the signal conditioning circuit.

So, when I briefly describe about fundamental functions, one advantage of having signal conditioning is amplification. So, you can – amplification, isolation between your input stage and the output stage when the recorded signal has a noise, the signal conditioning system should have ability to filter out the noise and extract the useful information from the actual data then in few cases when you see not all the sensors or not all the transistors can provide an output in terms of voltages.

So, when I say a sensor it can be an electrical signal. What I mean by that is that the output variation need not to be always voltage, it can be any change in the resistance, any change in the current, any change in the inductance, any change in capacitance too but it is an electrical change, electrical parameter change.

But the change offered by the sensor cannot be detected by the ADC because ADC requires only voltages and input or into the next stage whatever we do cannot identify the changes in the resistance or current or inductance or capacitance. So, sometimes it is also required to convert the change in the current or the resistance or the capacitance or the inductance into voltages too.

So, such a way you require to have excitation voltages. Then linearization in case if the data that you receive is not linear and if you want to make it linear so that it is easy for further processing. Some kind of linearization techniques also will be implemented which will come under, fall under the signal conditioning circuit too.

Now for example say imagine we have a sensor, which gives an output voltage, which gives an input in terms of a resistance change. For example, as we have already discussed one such example as a temperature sensor, when I say LM35, LM35 is a semiconductor based temperature sensor where it will directly give an output in terms of voltage. But we have also seen all the sensors need not to give an output in terms of voltages too.

For example, say if you consider RTDs, for example say PT100. PT100 will give an output in terms of resistance change, thermistors that also gives output in terms of a resistance change that means any change in the temperature will change its resistance. AD590, which is also another type of temperature sensor that gives output in terms of a current change.

So, imagine given the situation where you do not have an output change in terms of voltages but where you have output change in terms of resistance or current or even if we have an output voltage of 10 millivolt per degree centigrade where every 1 degree change in the temperature will change the output by 10 millivolt. Given new situation and if you directly interface this 10 millivolt to an ADC imagine how much – how many levels of ADC that you are going to utilize and what is the complete system.

Or giving you another situation where you always have an offset. For example, say you have the output voltage of the sensor will be between 1 volt to 3 volt the span of your ADC somewhere around 0 volt to 2 volt. So, when I directly interface 1 volt the range of sensor directly to the ADC this is the ADC span whereas the – this is the output voltage from the sensor; span of sensor.

So, when we directly interface so it has even though the change the offset the change between the maximum and minimum is 2 volts and the ADC is also capable to measure the 2 volts because of this 1 volt offset, the ADC cannot measure a complete range that output range that the sensor is providing it. So, as a result, because of these mismatches, you will be losing the data or the accuracy of the system is – the range of the system in this case is completely compromised.

But if we can somehow increase, somehow compensate for the offset created by the output voltage such that subtract the complete voltage with 1 voltage so that the complete span of the sensor will be now 0 volt to 2 volts will completely match with respect to the ADC span when we directly interface during such a situations, you do not have to even compromise, compromise on your the range of your ADC too.

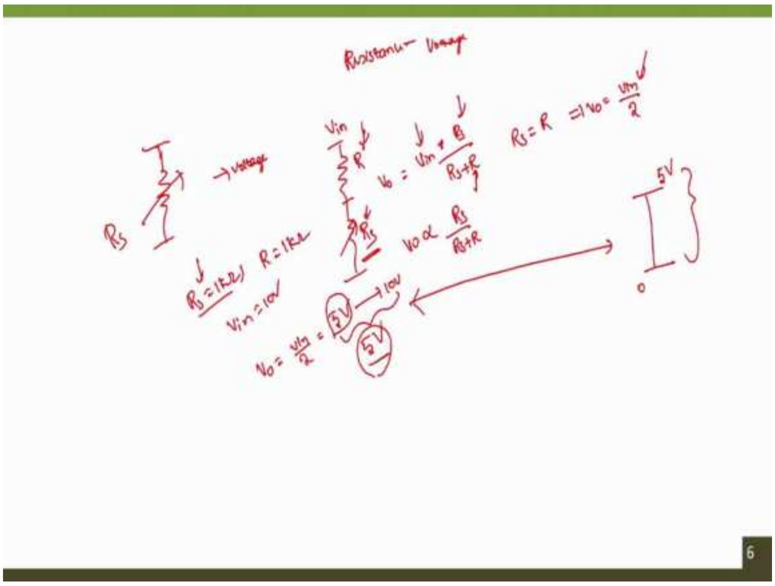
So, such a small variation, such a small understanding the difficulty when we are interfacing and compensating according to that is the role of signal conditioning so that you can accurately measure, and we can improve the complete system accuracy as well as the range too sometimes. So, in this case when I deal with 10 millivolt, so when you say your maximum temperature to be measured of 50 degree and when you look into the output voltage, you will get somewhere around 0 volt to 50 into 10 millivolts. That means 500 millivolt, 0.5 voltage. So, even though you have a range of ADC of 0 to 5 volts, you could use only 0 to 0.5 volts.

So, see how many level, suppose say if you are taking ADC of low bits, this 0 to 0.5 volts will fall under either variation in one bit or 2 bit not more than that or if you want to – if you require, if you are looking for very good resolution, very good resolution of the complete system output you have to go with the higher bit.

Rather than doing that, if we can amplify the input voltage signal by a factor of 10 so that 0.5 will be multiplied with 10, so that you will get 5 volts and if you map with respect to the levels of, map with respect to the range of your ADC, finally you can utilize the complete levels of an ADC and the complete accuracy of the system will be improved with a lower order, lower bits of your ADC itself. So, that is the rule of a signal conditioning circuits in most of the interfacing systems.

So now, so we have seen some examples with respect to when there is a change in the output and when there is a change in the levels, when there is a difference in the levels. For example say you have a temperature, you have a sensor which gives resistance change and you know that resistance change you cannot directly interface to an ADC, you cannot interface to an ADC.

(Refer Slide Time: 25:38)



So, how do we do that? So, imagine this is your sensor, so the arrow indicates that it is a variable, R_s, so R_s represents the sensor resistance. How do I convert into a voltage, so you should always think about the conversion of resistance to voltage. So, resistance to voltage conversion is also a part of a signal conditioning circuit where it is creating a bridge between the output of your sensor to the input of your ADC. Hope you may not get enough thoughts about this right now, but when I discuss about what are the different ways you understand that these are the basic circuits that we have already dealt in 10th class or 12th class.

One simplest way to convert your resistance to voltage is by using a simple resistive divider network. So imagine, I put this resistance in a resistive divided network where the V_{in} is an input provided to the system and R is your fixed resistance and R_s is the sensor resistance. Now as you already know the calculations of the resistive divider network, we know that

$$V_0 = \frac{V_{in}.R_s}{R_s + R}.$$

That means what we can see suppose say if V_{in} is fixed R_s which is a resistance offered by the sensor, which will be always varying and R_s fixed. We can clearly see that,

$$V_0 \propto \frac{R_s}{R_s + R}.$$

So, if R_s and R, R_s and R is equal, then the

$$V_0 = \frac{V_{in}}{2}.$$

So, this R not only helps to convert your resistance change offered by the sensor to a voltage, it can also be used as a current limiting circuitry or a protection circuit for your sensor too. So, both requirements one is the - in order to avoid to operate for a higher currents, as well as to convert your resistance to voltage a simple resistor can help you to do that too.

So, but designing the resistance value choosing the proper resistance value is always important that depends upon the power requirements of your sensor. But our whole idea was to convert the resistance. Of course, you have already done that. So, why do not we directly use this resistance to voltage conversion and directly interface it to an ADC?

Yes, of course, you can do but one catch here is that when we deal, when you are looking into the resistance to voltage conversion the minimum voltage that you will get will be $\frac{V_{in}}{2}$ or the maximum voltage will be $\frac{V_{in}}{2}$. It depends upon where your R_s is being connected and where is R_s connected and where the output voltage you are measuring it to.

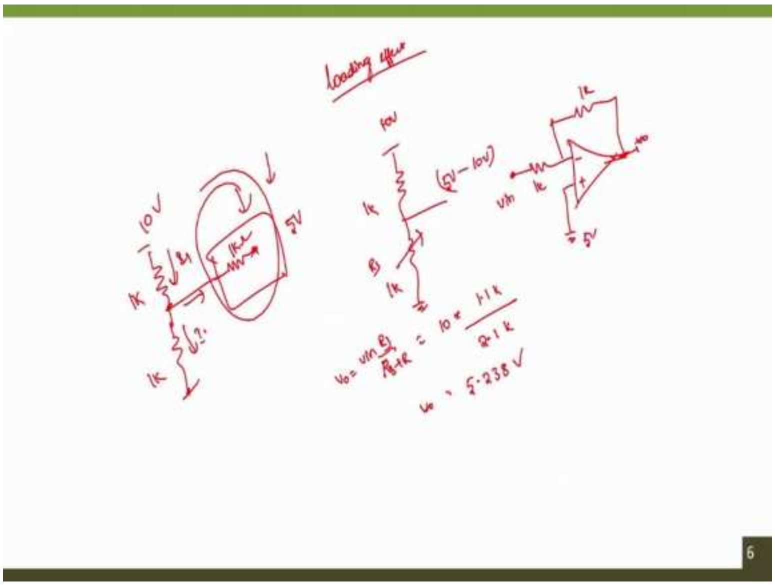
So, that means the total range will be half of your input voltage. So, that means half of the levels are, for example say, my R_s is 1 kilo ohm, so R I am considering as 1 kilo where V_{in} is nothing but 10 volts. So, V_0 will always start from see R_s when I say 1 kilo ohm. This is the base resistance offered by the sensor which means any change that you observe will be with respect to 1 kilo, so 1.1 kilo, 1.2 kilo, so the changes 200 ohms, 100 ohms, but the base resistance will also add up to your change.

So, that base resistance is nothing but 1 kilo. So, the total $V_0 = \frac{V_{in}}{2}$. That means the output voltage will start from 5 volts, 5 volts to 10 volts. What is the total range that you have? A total of 5 volts. But what is the span of ADC suppose if the ADC range of 5 volts and ADC is operated at 5 volts, the total span of your ADC input is of 5 volts.

Of course, the change that you observe is also 5 volts. But ADC range is also 5 volts. It may match but due to the offset initial offset providing initial offset from the resistor, base resistance and the resistance that is chosen by sensor you cannot directly interface into this. But how do we, how can we compensate for this effect? Simplest way is offset the output voltage from the resistive divider network with 5 volts.

So, in order to do that functionality, we have a different electronic circuits. Again a design of signal conditioning circuits play an important role. One way in order to avoid that is to remove this offset is by using operational amplifiers. The reason why most of the signal conditioning circuits uses an operational amplifiers is that it has very good specifications in terms of input impedances, output impedances, CMRR. Because of these inherent properties of the operational amplifiers, most of the signal conditioning circuits utilizes Op Amps as one of the crucial part in the circuits.

(Refer Slide Time: 31:26)



So, the reason I will tell you simply. For example, I have a resistive divider network and the output is connecting to a system. When I talk about any system, any system will consume some kind of a current and by providing some kind of a voltage that means it will always have some kind of input impedance. Input impedance and output impedance are some of the important characteristics of any system.

So, when I say the input resistance or input impedance of the system is of 1 kilo ohm. So, this is also 1 kilo, this is also 1 kilo, and this is of 10 volts, what will happen you are expecting to see an output voltage of 5 volts but you may not get output in terms – the output when you measure out, it will not be 5 volts anymore. That is because of the input impedance offered by the next systems.

But replacing the system with directly connecting the output of the resistance divider network to a terminal of Op Amp will solve your problem because Op Amp has a very high input impedance. That is why when you consider a multi-meter directly connecting across this terminal you will not see any losing of the data the reason is any measurement circuits will always have the very high input impedance. You can further refer into the data sheet of the measuring devices where they will always specify in terms of mega ohms of your input impedance.

The intension of having mega ohms is that the current drawn by the circuit will be very, very, very small. Ideally speaking it is 0. So, whatever the current that you are getting will be will not have any change in the input current and the output current because of connecting a simple external circuitry that is very much important when we are designing a signal conditioning, conditioning circuit. There should not have any mismatches are drawn by current or the power consumed by the input source.

As a result, if there is consumption of the power from the input, it can be in terms of voltage or the current the information of the input will be lost when you are transmitting into the next stage. So, this is nothing but your loading effect. So, when we are designing a circuit, make sure that it is not loading your input, when it happens you are losing the information. So, that is the major characteristics of any subsystem when we are interfacing between 2 different subsystems. These always have to be remembered.

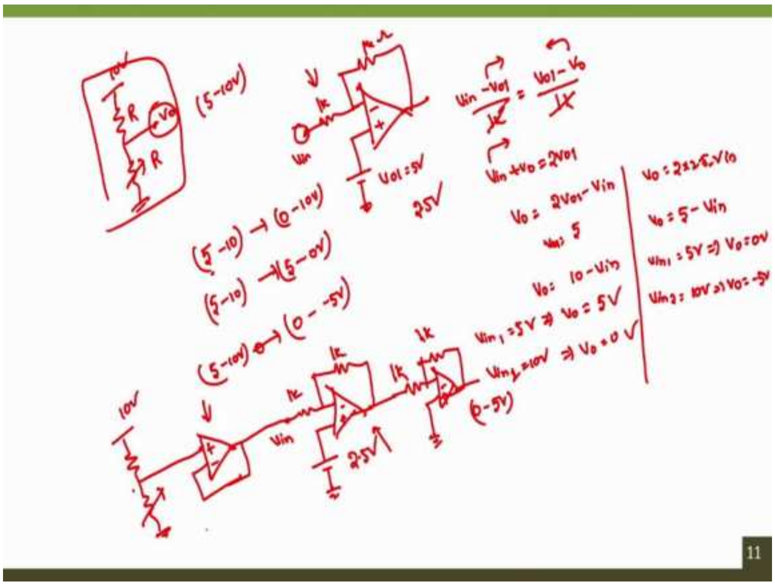
So, we have already understood that the input impedance of the systems should be always high good. Now, so this is 10 volts, 1 kilo, 1 kilo. So, what I will do rather than me directly now image that I have 10 volts. So, what do I get if it is 1k, 1k, 5 volts and most of you are aware it with operational amplifiers I hope so when we are dealing with inverting amplifier configuration, so the output voltage when there is an increase in the resistance will be in terms of 5 to 10 volts maximum.

So, because

$$V_{out} = \frac{V_{in}.R_s}{R_s + R'}$$

so imagine this is 10 R_s is say 1.1 k and 1.1 so 2.1 k, which is equal to 5.238 volts. So, any increase in their resistance will automatically increase your output voltage too. That we can clearly see that. Now say I want to offset it. One way of offsetting is say if I connect it, this is 1 kilo, 1 kilo, V_0 so instead of connecting here with a ground if I connect it to 5 volts, and say this is V_{in1} so what will be the effect.

(Refer Slide Time: 35:38)



So, when we solve this, $\frac{V_{in}-5}{1k}$. So, just to solve this I will consider input as V_{01}. Now let me try to solve this. So, it will be $\frac{V_{in}-V_{01}}{1k} = \frac{V_{01}-V_0}{1k}$. 1k, 1k cancelled so $V_{in} + V_0$ so I am taking V_{out} in this direction, V_{01} in this direction, which is equal to $2 \times V_{01}$ so since I need V_0 and I am taking V_{in} in this direction, $2V_{01} - V_{in} = V_0$.

So, since in order to utilize the complete levels of an ADC, we require to use 5 to 10 volts. We should convert this 5 to 12 volts to 0 to 10 volts adding a 5 volts as a V_{01}, as an offset voltage makes V_{02} to be 10 - V_{in} which means that when an input voltage of 5 volts when the input voltage of this 5 volts is connected here, for V_{in1} which is a 5 volts that implies V_0 we will get it as 5 volts whereas for input voltage of 10 volts, we get V_0 as 0. Of course it is converting 5 to 10 volts to 0 to 5 volts but it is in a reverse fashion which means that 5 to 10 volts is converted to 5 to 0.

If this is okay, we can simply use a V_{01} as a 5 volts. But this reversing order again in the next stage we may have to compensate for this reverse order. Else the results would completely change or even in the microcontroller programming if in case if we use, so we have to compensate for this reverse order, swapping. So, rather than that if we can design another way of using it, is in stead of using V_{01} as a 5 volts, considering V_{01} as a 2.5. So, when we consider V_{01} as 2.5 considering the case 2 so $V_0 = 2 \times 2.5 - V_{in}$ which is nothing but $V_0 = 5 - V_{in}$.

So, case 1 again when V_{in1} = 5 volts, that implies $V_0 = 0$. Whereas when V_{in1}, V_{in} = 10 volts, V_0 we get it as 5 - 10 - 5. So, this gives us a negative 0 to so 5 to 10 volts is being converted to 0 to - 5 volts. Of course, this is negative sine we are using an inverting amplifier configuration because of which we are getting a negative sign.

However, again this negative sign can also be inverted by using a simple inverting amplifier configuration with a gain of 1. So, what I mean is that if I use another inverting amplifier configuration, here the offset voltage is 2.5 volts 1k, 1k then V_{in}, then again I will be considering 1 more inverting amplifier configuration with a gain of 1, 1k, 1k.

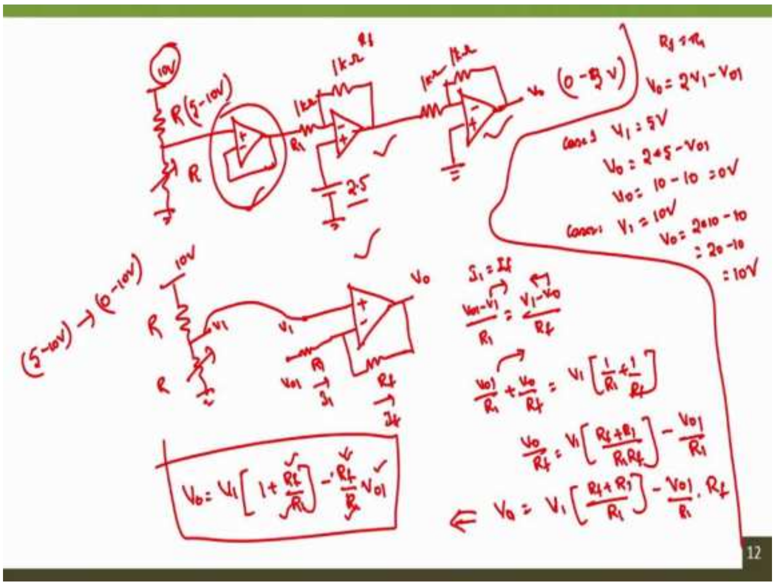
So, for input voltage of 5 to 10 volts we will get an output of 0 to 5 volts within the same phase. Because single operational amplifier because of an offset and because of inverting amplifier configuration thought it is providing the required voltage 5 to 10 to the offset of 5 volts - the offset of 5 volts can be completely eliminated but it is creating a shift in the signal.

So, to avoid the face shift again if you use an inverting amplifier configuration where it has a phase shift of 180 degree because of that phase shift again the minus will convert to the positive so 5 to 10 volts can be directly used as 0 to 5 volts this is one approach. So, as we have already discussed previously, one advantage as we cannot directly connect to V_{out} a terminal directly to the V_{in}, the V_{out} cannot be directly connected to the V_{in} because of the input impedance offered by the system.

So, one way to avoid the problem is as we have already seen we can use a simple inverting voltage follower configuration where the input will be directly connected that means, the output of the resistive divider network circuit, so can be – the output of the resistive divider network circuit can be directly connected to the positive terminal and since it is connected directly to the positive terminal of an operational amplifier the input impedance of the complete system is also high because the non-inverting terminal or any terminal when we are directly connecting it to the terminals of an operational amplifier the input impedance will be very, very high.

If you look into the data sheet it will be somewhere around 10 mega or even more, it depends upon IC that we have considered. Then the output can be directly connected so this solves the problem of input impedance. At the same time, this offset which is being generated by this resistive divider network circuit can be completely removed or completely eliminated with the help of another 2 operational amplifiers too.

(Refer Slide Time: 41:45)



So, let me redraw the circuit. So, the final circuit will look like as follows, 10 volts, 1k, so if I see this as a sensor, this is also R this is also R, R what I mean in the sense in initial or base resistance, so we use voltage follower configuration then we use inverting amplifier configuration with a gain of – with an offset of 2.5 and $\frac{R_f}{R_1}$. Of course, it depends upon the gain that you require you can adjust the R_f and R_1 values.

This is R_1 and this is R_f so that in case if you require a higher gain and if you want to utilize the complete levels of an ADC, the amplification will always help and to remove the offset to remove the phase shift again we use another operational amplifier with a negative feedback configuration at the same time with a gain of 1. This will completely solve. This will completely convert 5 to 10 volts which is having an offset of 5 can be removed and we can achieve 0 to 5 volts as an output, linear varying output.

Great of course when you look into that is this only the configuration that we can build? No of course there are different ways of doing this. This is one approach. Another approach would be minimizing the optimizing the complete circuit. What I mean by optimization? In this case if you observe the number of operational amplifiers that we use or the number of resources that we are using it.

Why do I have to consider this because when you say a 2.5 so the complete circuit is operating with 10 volts when I consider it again you either have to design another circuit that can provide output as a 2.5 or you have to consider another voltage source to have an output voltage of 2.5 which can be provided as an input to the positive terminal. Of course, you can use another resistive divider network configuration to do the same.

So, because of which the number of elements or the number of resources that you are utilizing in this circuit is high. One way to optimize this instead of using a simple 3 different operational amplifiers we can simply go with a simple non-inverting amplifier configuration 2. Since in case of a non-inverting amplifier configuration as the output from the previous stage will be connected directly to the input to the input of the non-inverting terminal of an Op Amp, this solves the loading effect.

This solves the problem that we faced in the previous case which is of low input impedance. So, how the circuit looks like so one way is using this. So, say this is R and this is also R but this is a sensor and this is a 10 volts of course we have to design the circuit we have to select the resistance in such a way that this 5 to 10 volts will be converted into 0 to 5 volts.

So, but when you look into the non-inverting amplifier configuration, as everybody would be aware, so operational amplifier should always be in a negative feedback configuration in order to reduce gain of overall gain of op amp and whereas the inverting terminal which is connected to R_1 resistor should be always connected to the crown. So, instead of connecting it to the ground, just I will consider this as V_{01} this as V_1 so this is also say V_1.

Now if this is the case, so as we have already seen in the previous one. So, V_0, solving for the V_0, we know that if I say this is I_1 and this is if so I_1 is equal to if ideally speaking. So,

$$\frac{V_{01} - V_1}{R_1} = \frac{V_1 - V_0}{R_f},$$

so taking V0 in this direction, even in this direction, $2V_1$, if $R_1 = R_f$, R_1 R_1 can cancel due to the let I do not consider R_1 and R_f as same.

So, R_1 R_f so if I take it in this direction, $\frac{V_{01}}{R_1} + \frac{V_0}{R_f} = V_1$ if I take a common $\frac{1}{R_1} + \frac{1}{R_f}$. So, since we require to get a relation between V_0, V_1 and V_{01} so taking V_{01} in this direction which will become

$$\frac{V_0}{R_f} = V_1 \left[\frac{R_f + R_1}{R_1 R_f}\right] - \frac{V_{01}}{R_1}.$$

So, that implies

$$V_0 = V_1 \left[\frac{R_f + R_1}{R_1}\right] - \frac{V_{01}}{R_1} R_f.$$

So, this can be rewritten as

$$V_0 = V_1\left[1+\frac{R_f}{R_1}\right] - \frac{R_f}{R_1}V_{01}.$$

This is what we got.

So now, what we have to do we know that when we have to design, we have to select a proper offset voltage of V_{01}, as well as the resistance values of R_f and R_1 in order to achieve, in order to get output as 0 for 5 volts and output as 5 for 10 volts. So, in order to do that, so let us for a simplification, I will consider $R_f = R_1$ so when I consider $R_f = R_1$, so we can write it on as $V_0 = 2V_1 - V_{01}$ which is similar to what we have seen in the previous case.

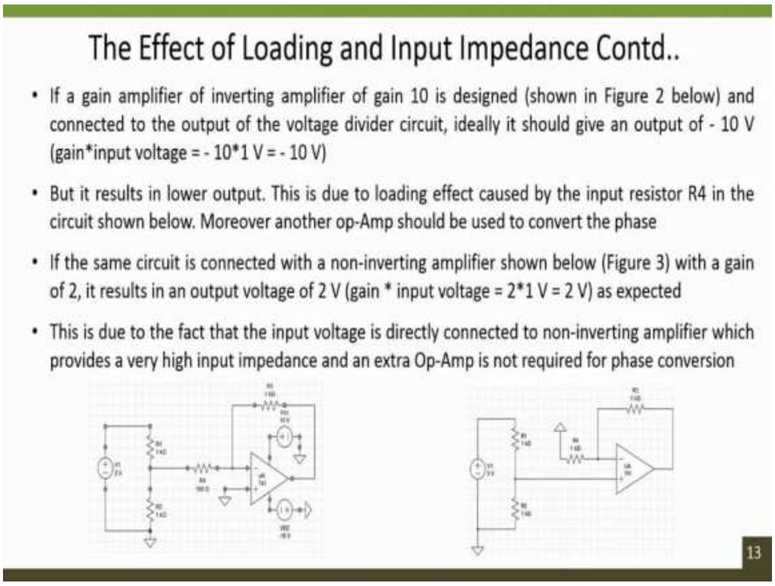
Now when I – now what we need case 1. What should be the value of V_{01} and in order to get V_0 as 0 for a V_1 as 5 volts so when I consider this $V_0 = 2 \times 5 - V_{01}$. So, $V_0 = 10$ - if I consider 10 yes I get 0. So, for input of 5 I get 0 again, then another one, case 2, when $V_1 = 10$ volts, when $V_1 = 10$ volts we should get 5 as an input.

So, when I say V_0 so it will be $2 \times 10 - 10$, so which means that 20 - 10 we get output as 10 volts. So, what is happening here, here 5 to 10 volts is being converted to 0 to 10 volts but what we require 5 to 10 volts should be converted to 0 to 5 volts, but it is having an amplification, it is having an amplification of twice that of what we have seen in the previous case.

But using a single amplifier op amp, operational amplifier connecting directly the V_1 output to the input of non-inverting amplifier we can avoid the use of voltage follower configuration and if this 10 volts, 0 to 10 volts is good enough we can simply use a single operational amplifier to solve the problem. So, this is another approach of how we can solve this.

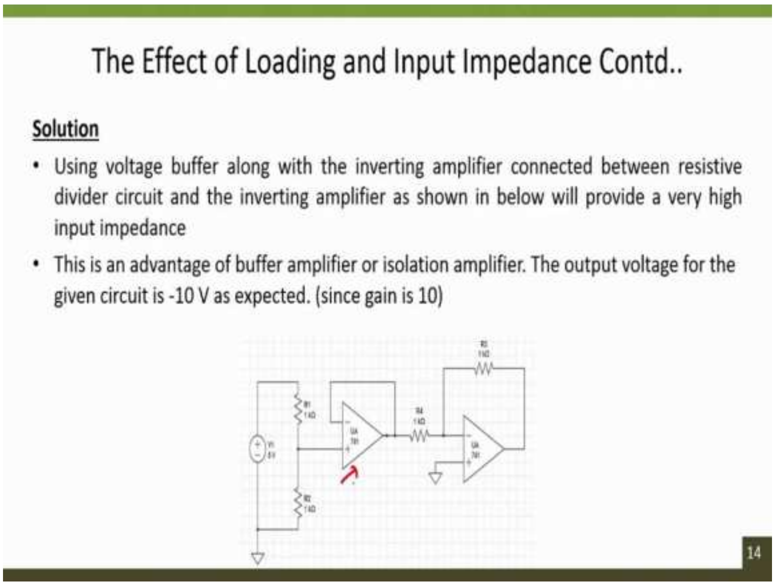
Next, is this the only way? No, you have of course if you want to reduce the offset, if you want to reduce the gain again at the output stage, you can have attenuator with a gain of $\frac{1}{2}$, 0.5 with a gain of 0.5 so that the 10 volts into 0.5 it will become 5. So, you can remove the offset or if you can properly choose the values of R_f and R_1 such that any voltage when the input voltage of 10 volts to get an output of 5 properly choosing your Rf and R1 we can even solve that problem, so this is another approach.

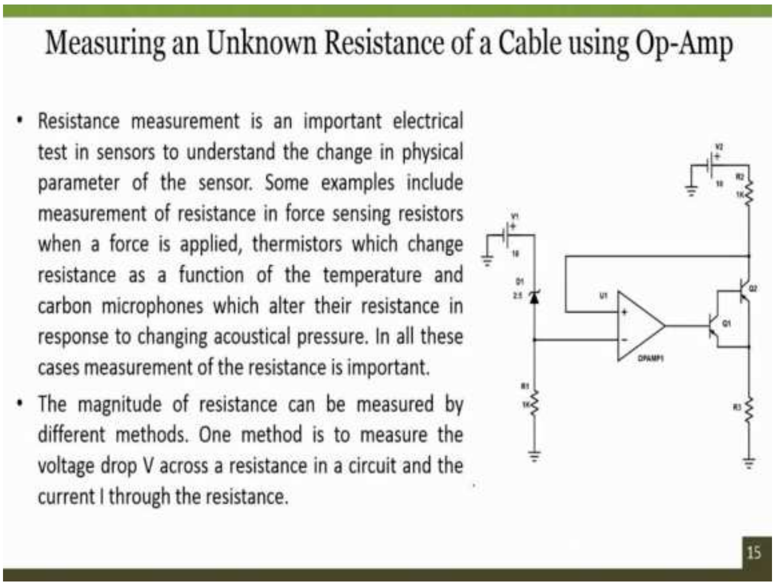
(Refer Slide Time: 51:20)



So, this is what we have seen in the effect of loading an input impedance, why it plays an important role when we are designing, when we are interfacing 2 different subsystems and if those subsystems are not matching with respect to the loading parameters, with respect to those input and outputs are not matched the output will drastically change, the expectation that we the output voltage will not be within the limits of what we have plan to design.

(Refer Slide Time: 51:50)





So, as we discussed one way to avoid this problem is by using voltage follower configuration or instead of using a inverting amplifier configuration just go with a non-inverting amplifier configuration.