Circuits for Analog System Design

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Module No. # 08

Lecture No. # 37

MC Based ADC

Today's lecture, we will continue our discussion about sample and hold amplifiers. We were discussing about succession approximation ADC and its usages and then in that connection, we were discussing about sample and hold amplifier.

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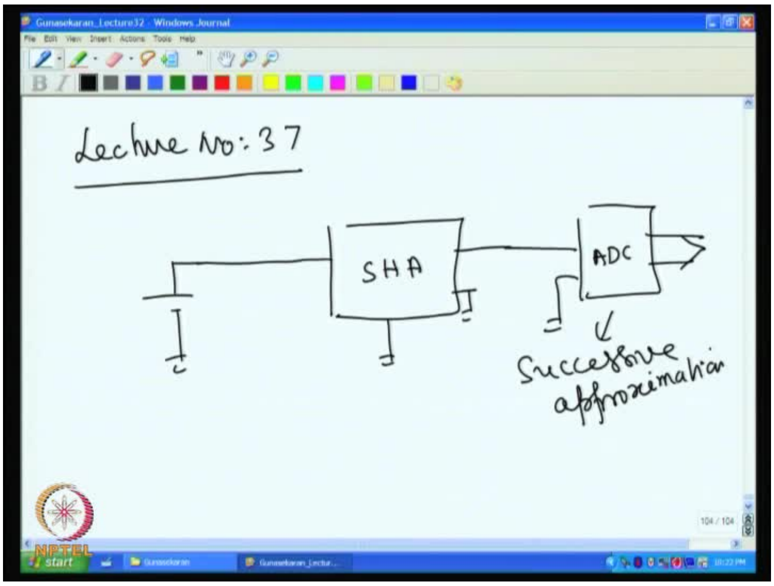

So, essentially, if I had to digitize some analog input voltage, then we have an analog input voltage that is given through a S H A amplifier. It is given essentially Then the output of the S H amplifier is given to A to D converter. That is the scheme and then you get a digital output from the ADC.

So, in this connection, this we are here we are discussing about successive approximation ADC. we are discussing and We had shown in the previous class, how the successive approximation ADC is working and why we need a sample and hold amplifier and we were discussing about sample and hold amplifier in the previous lecture.

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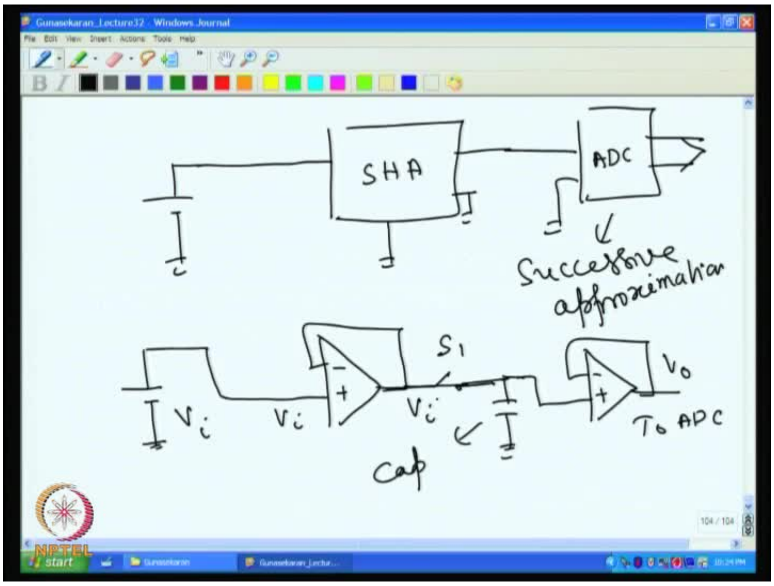

So, if you see in the previous lecture, the sample and hold amplifier essentially holds the voltage in the capacitor. If we see the digital circuit of this, you have an input voltage that essentially is given through a amplifier. We want to actually charge the capacitor. One possible circuit is that we can have a very small capacitor connected here and then at the output. So, we will have a for example, switch here. Then essentially, what happens is V i and then the switch S 1 and then the output; this is to ADC.

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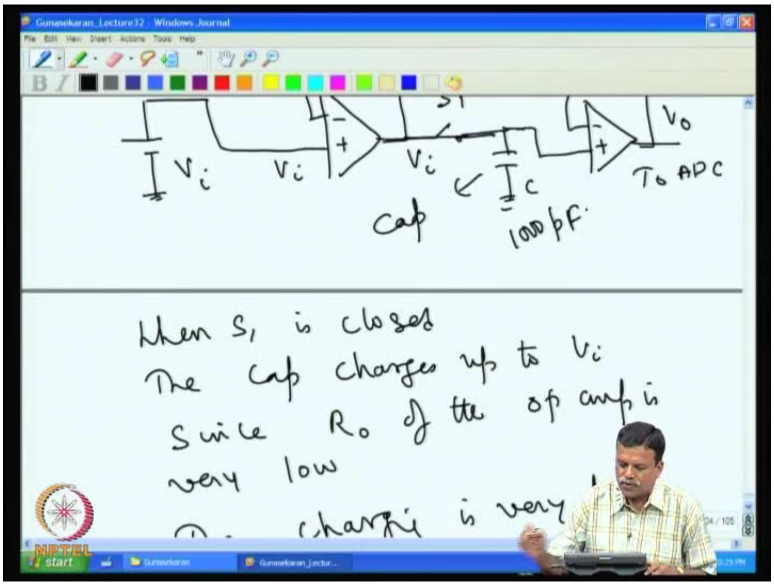

So, this is the hold capacitor which charges up. So essentially that V i here, comes as V i at this point when switch S 1 is closed. When S 1 is closed, the capacitor C charges up to V i. This needs some time to charge up, but the output impedance of the op amp is small, since R 0 of the op amp is very low, the charging is very fast

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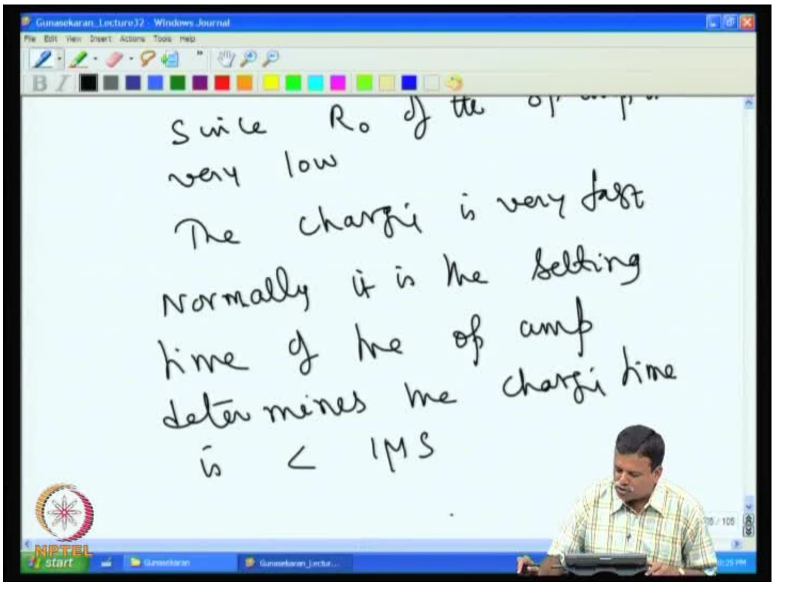

Essentially, few milliohm resistance and then few less than 1000pf capacitor charges up in a fraction of a micro second. Normally, it is the setting time of the op amp that determines the time constant - setting time of the op amp determines the charging time. After that Normally, it is less than 1 micro second. So, here, the charging is very rapid. Then once it charges up, then switch off S 2, switch off S 1.

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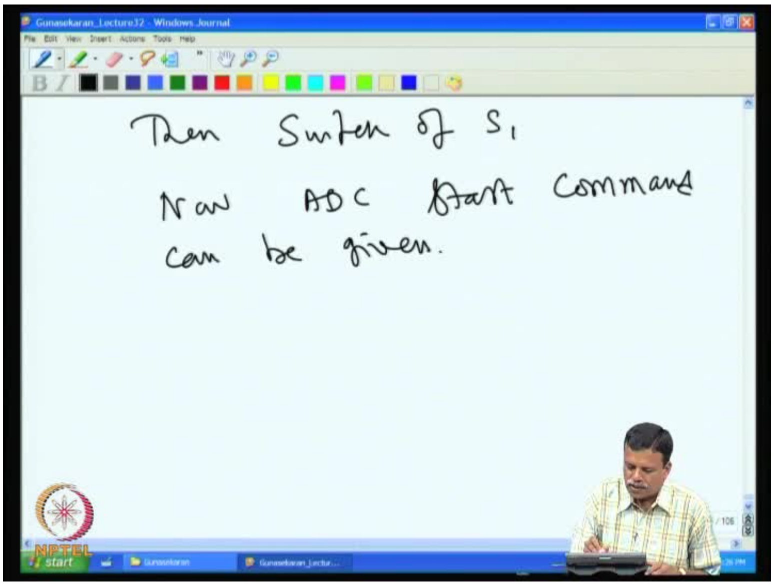

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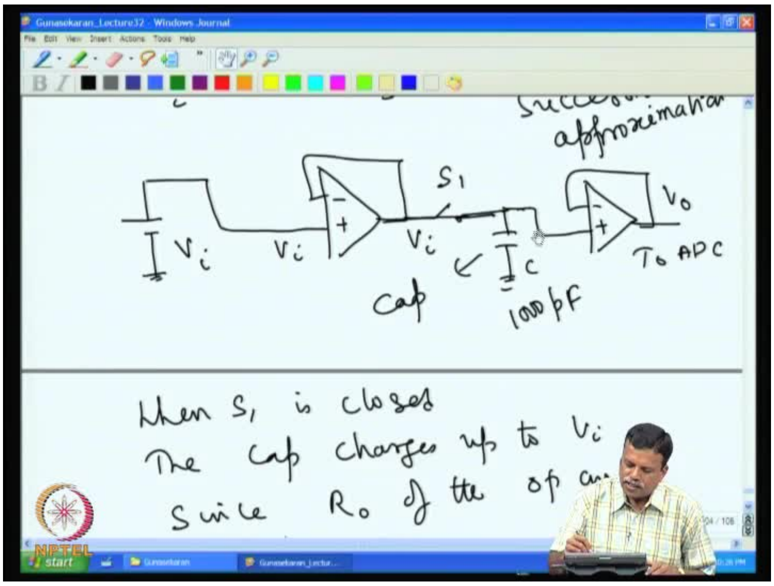

Now, ADC start command can be given. During the conversion, the voltage and the capacitor should not come down because if the capacitor is too small, then the input resistance of the op amp discharges this. So, during the conversion time, capacitor should not lose too much charge.

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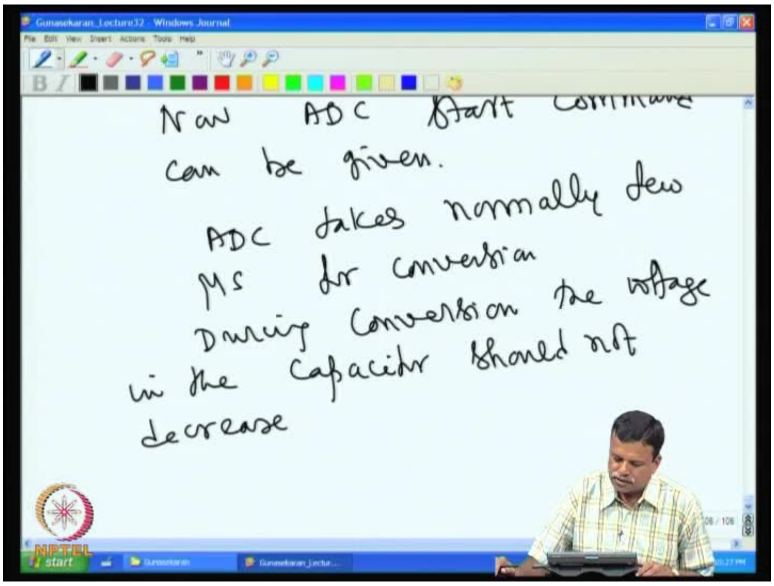

ADC takes normally few micro seconds for conversion. So, during conversion, the voltage in the capacitor should not decrease and it should have a low dielectric should not decrease and also it should have very low dielectric absorption.

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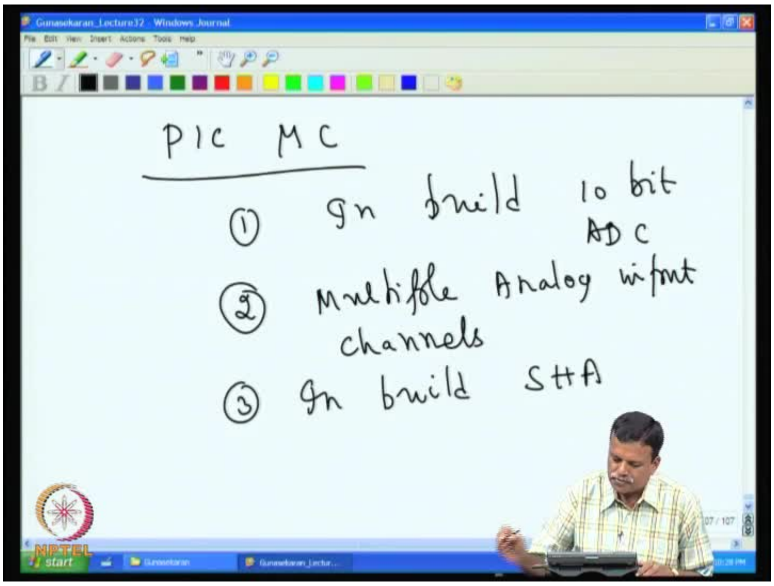

So, the sample and hold amplifier is essential for the conversion. now that is There are two types of sample and hold amplifier we can think of. If you see the conventional circuits today, take for example, pic micro controller. In case of pic micro controller, which has in built it has in built ten bit ADC and it has multiple channels, multiple analog input channels.

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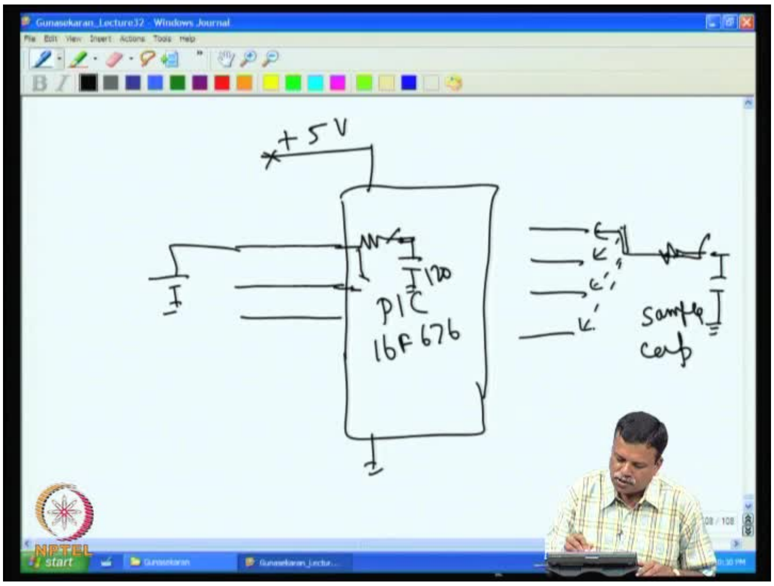

It also has in built ADC sample and hold amplifier; it has in built S H A. Let us see how one can use this one in the real life situation and that will explain the issues involved in the A to D converter. For example, if I take PIC micro controller, the most popular chip would be for example, 16F 676 micro controller. It has for example, many input channels analog inputs are there and then has a supply and then ground.

So V in is given in one of the channels and then this is actually connected inside through the capacitor and then there is a switch here - sample switch is there and also there is a switch for channel selection. We have a switch for channel selection. Essentially, if I draw this one, we have many input channels and we have a one output and then this switch actually connects either one of them, one of the channels can be taken from here and this actually goes through a resistance and then a switch and then to the sample capacitor.

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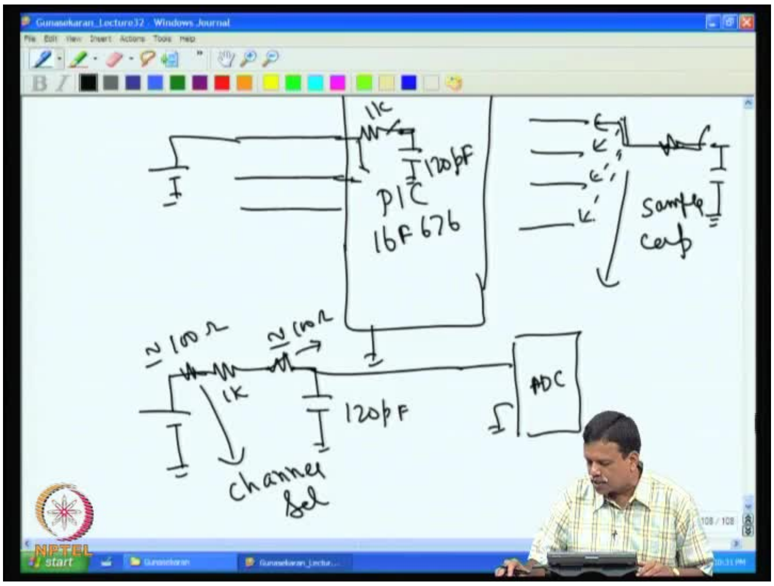

For example, in the PIC, 120 pF capacitor is there and this is about 1 K resistance is there and switch has some resistance. So, considering this, the equivalent circuit of the PIC micro controller looks like this. You have a 1 K resistance and then the switch and there is another switch and when that is on, if it has on resistance and it has another on resistance and then about 120 pF capacitor.

So, this is about 1 K; that is there in built and then this is about few 100 ohms and then this is also around few 100 ohms. So, about 1 K resistance is there in series to which charge up this. Then this ADC, the successive ADC is here. That is given as ADC input.

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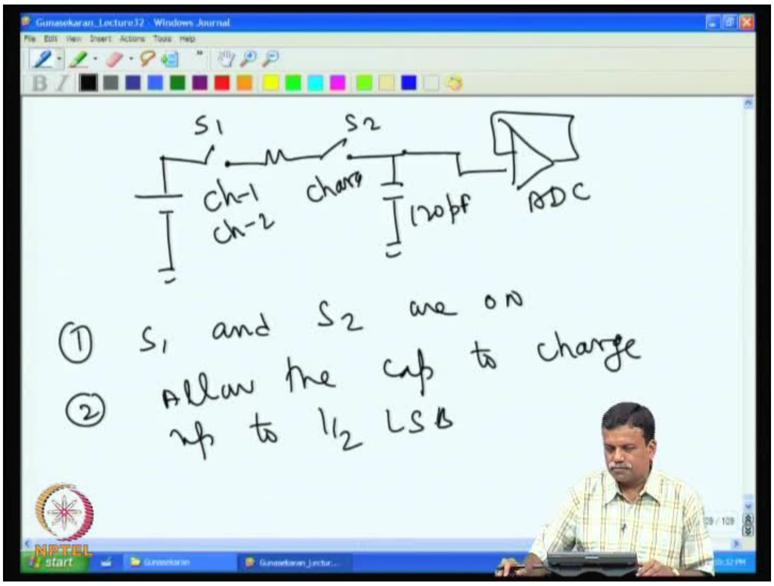

We have 2 switches one is for channel select; that is given here - channel select resistance and then this is actually to switch on and off the charging process. So, we can show it like this, in that case. We have an input voltage that comes through a switch, the resistance and then comes through a switch and then to the capacitor and then to the ADC. We make it ADC. So, you have channel selection switch and then charging switch. Channel 1, channel 2 whichever which you want can be selected and then 120pF of capacitor.

Now, if I had to do the conversion then first S 1, S 2. S 1 and S 2 are on - first. Now, allow the capacitor to charge up to half LSB because it is a ten bit converter. So, if it is a ten bit converter then we want 1 LSB accuracy minimum then I should allow at least the voltage to charge here up to half LSB so that I can allot half LSB error to this.

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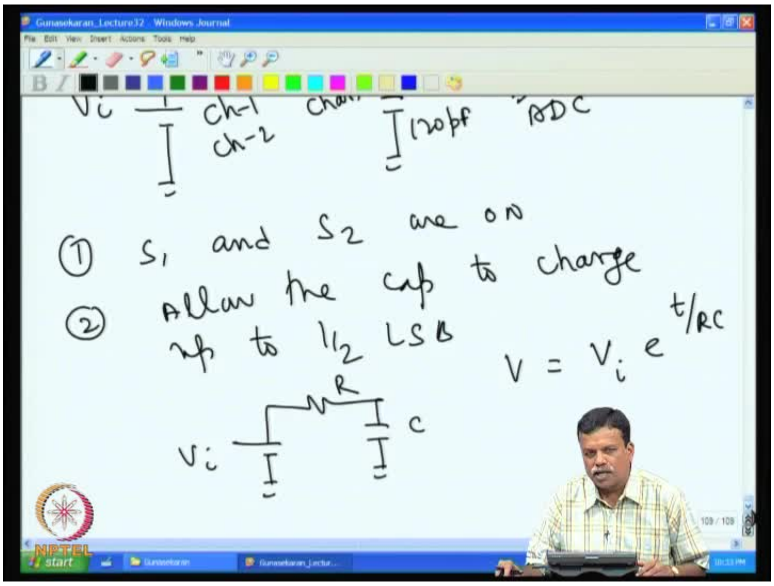

So, that means if V i is the input voltage, V i is the input voltage and then the capacitor charges exponentially. We have the input voltage and then the capacitor charges exponentially to V i. So, you have the voltage actually and the capacitor comes as V i into e power t by R C.

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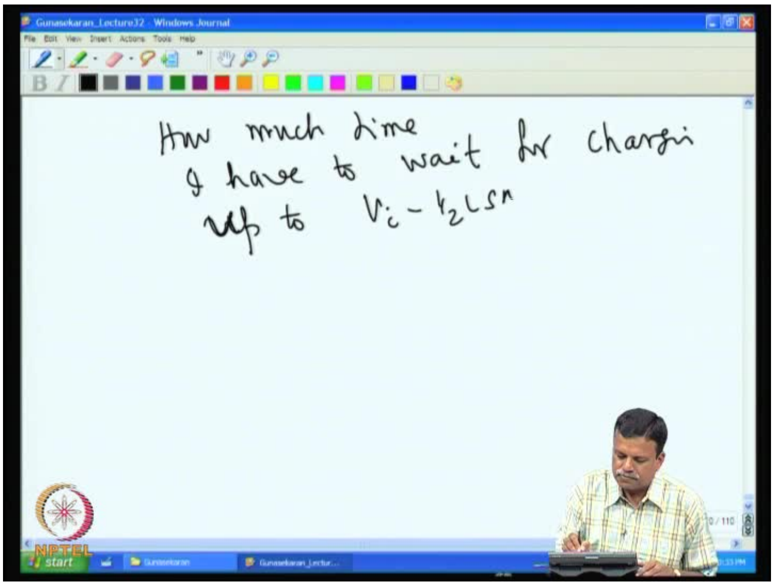

So, capacitor then the question is how much time I have to wait. That is, in the sample mode, how much time I have to wait? That is the question. So, how much time I have to wait for charging up to V i minus of LSB?

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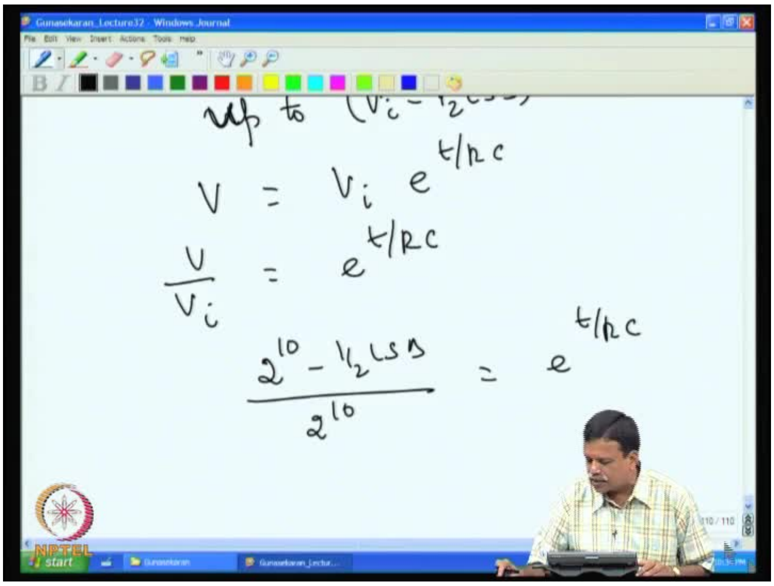

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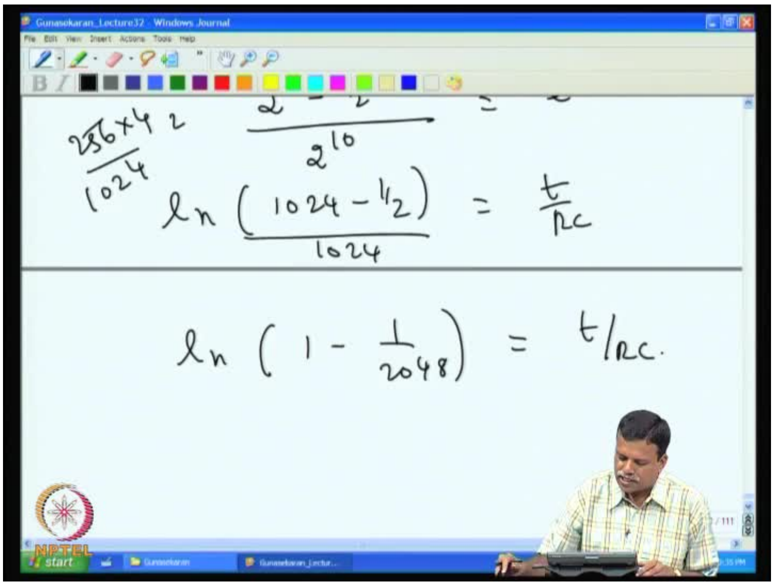

Now, that actually we can solve this equation and see that V actually comes as V i into e power t by R C. So, if I take this if I simplify this, you get this equation. Now, V by V i, actually V has to reach up to half LSB. That means, if it is a ten bit converter that will be 2 power 10 bits minus half LSB divided by 2 power 10. That is, the time that You get this one and if I take on both sides, then you will get it as l n of 2 power 10 comes as 1024 256 into 4, 24 2 22 2 into 1024 bits are there minus half divided by 1024 that comes as e power t by R C.

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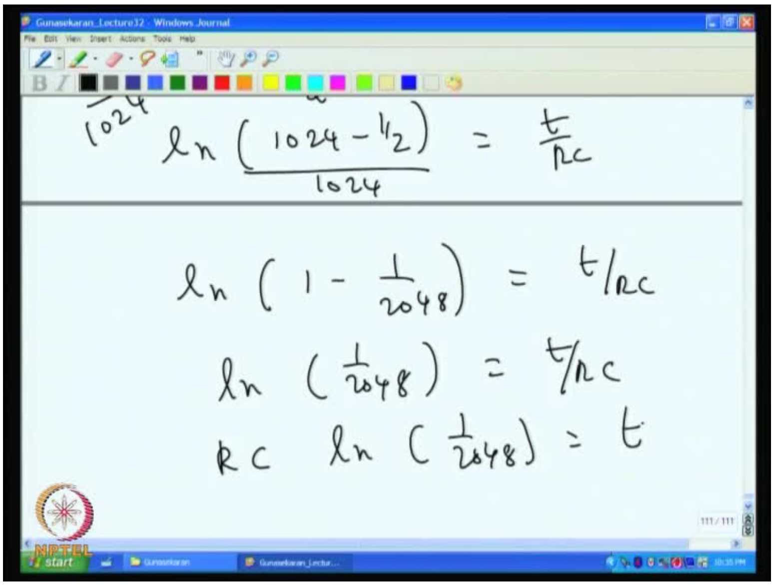

If I take that one, l n that comes as 1 minus 1 by 2048 and that comes as t by, this goes off here, and I have taken log here. So, that actually is t by R C and that comes as t by R C. So, that comes as l n 1 by 2048 equal to t by R C

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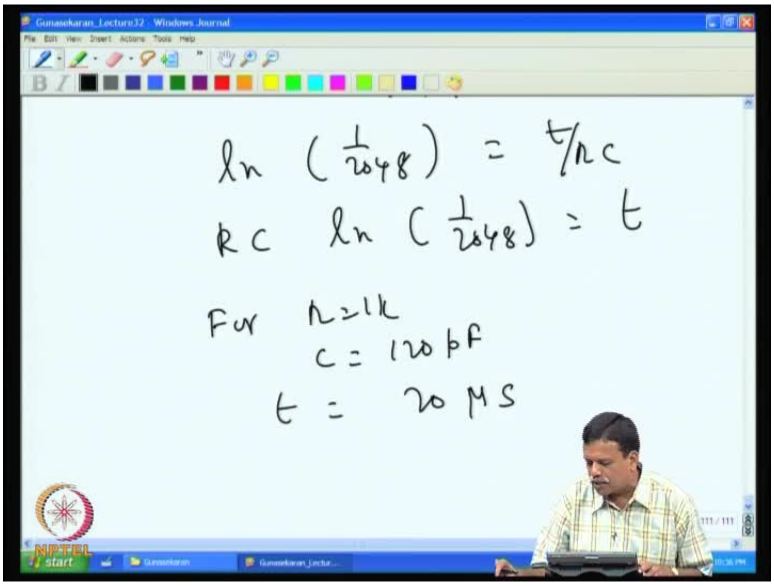

So, the t actually can be determined depending upon the time. So, this is the time t, I have to wait so that it charges. Normally, for this 1 K and about 120 pF error, you will find it is 20 micro seconds. For R is equal to 1 K and C is equal to 120 pF, this t comes out to be 20 micro second.

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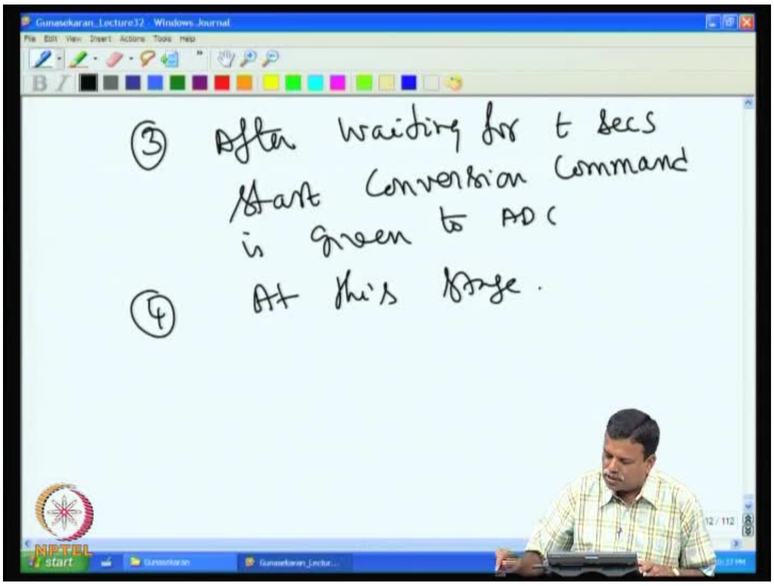

So, in this case, one has to wait minimum 20 micro seconds for the capacitor to reach half L S B. After reaching the half L S B, then I have to give a start command to the ADC. Then the third step would be after waiting for t seconds, start conversion should be given to ADC - start command is given to ADC.

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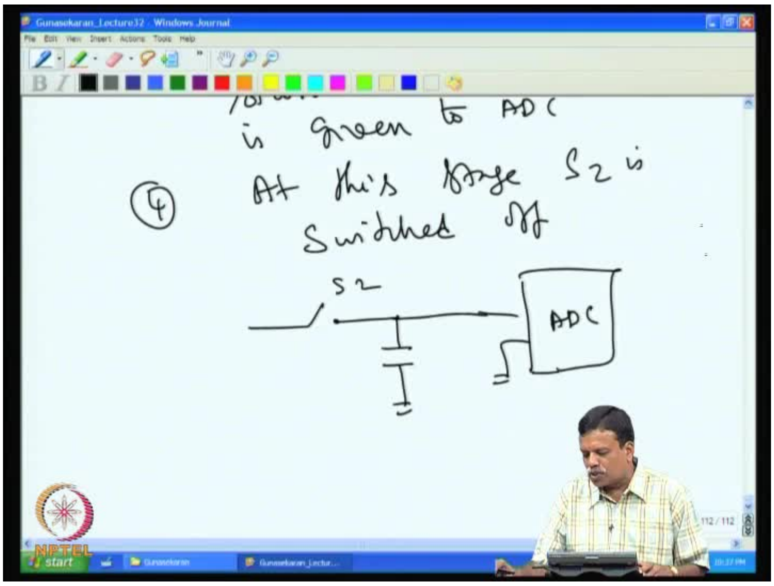

Now ADC also At this stage, the switch T 2 is switched off. Once start conversion command is given, then the switch S 2 is disconnected. Now, the capacitor is completely disconnected from the input and then the conversion starts. At this stage S 2 is switched off. So, you get the voltage, then you have the whatever voltage is there in the capacitor actually goes to ADC.

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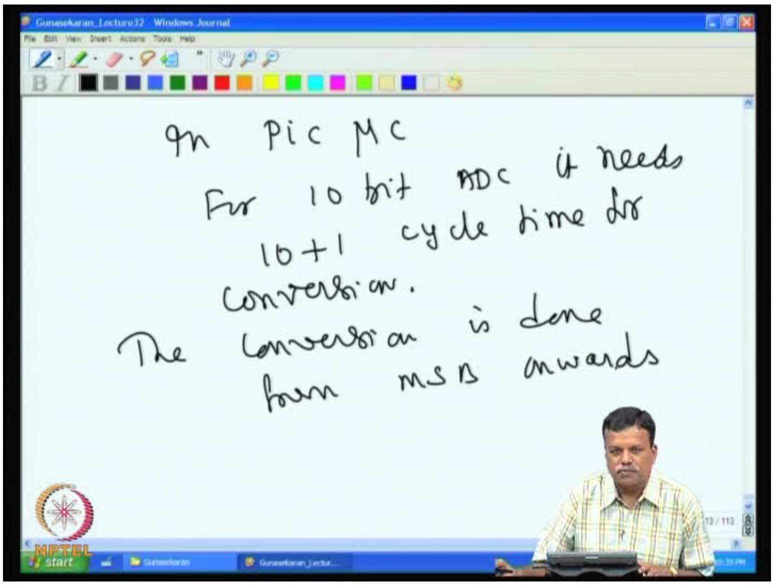

ADC takes its own time to work the conversion. For example, if you take PIC micro controller, in PIC micro controller mu c, for 10 bit ADC, it needs 10 plus 1 cycle time for conversion. So, at the end of every cycle, 1 bit answer is available. 1 bit cannot say answer because first. As we discussed earlier, the conversion is done from M S B onwards.

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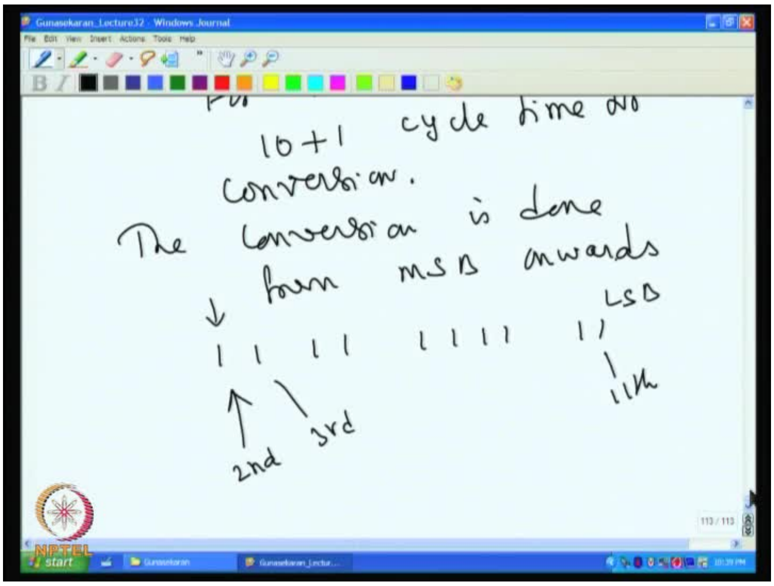

So, the conversion is done from the M S B onwards. Conversion is done from M S B - Most Significant Bit onwards. So, after say for example, if you leave the conversion first cycle, then after the second cycle, at the end of second cycle, you will have first M S B is ready; that is, higher end bit is ready. So, at the end of second cycle, if you take a 8 bit or a 10 bit converter, at the end of second cycle, your answer this bit is ready and then third cycle, this is ready and then the eleventh cycle, the converted bit, the LSB is ready.

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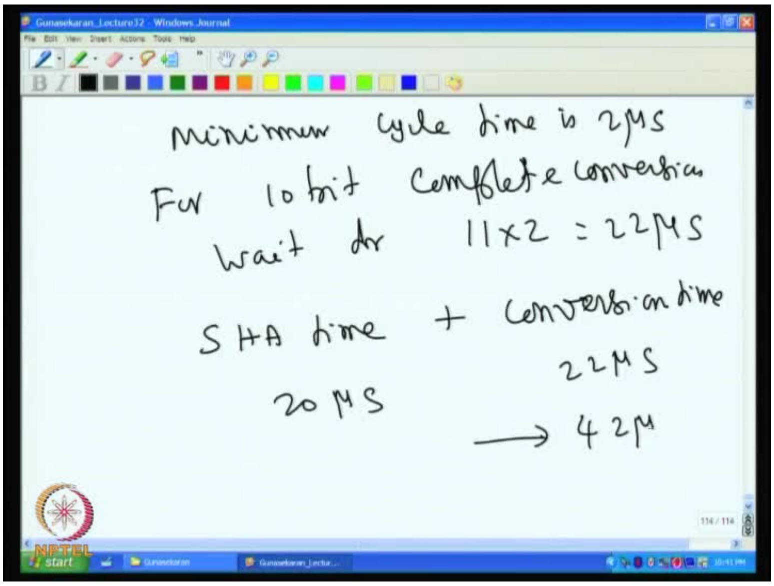

So, each cycle takes for example, minimum time is specified by the manufacturer. In this case, for example, minimum cycle time is 2 micro seconds, in this case. So, at the end of 20 that means for complete conversion, that is, if I want complete ten bit accuracy then I have to wait for 11 cycles - that means 22 micro seconds for 10 bit complete conversion. Complete conversion wait is 11 into 2 that is 22 micro seconds.

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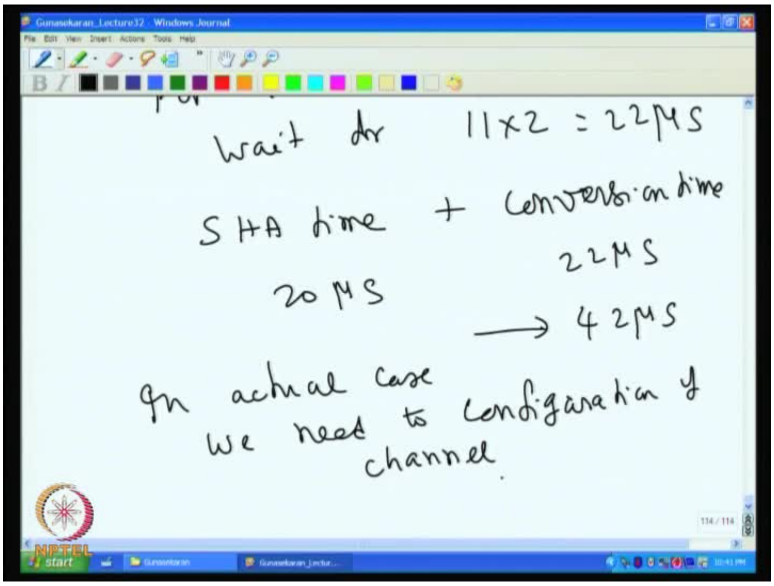

So at the end of 22 micro seconds, the conversion is over and then invariably the end of flag is set. So, the end of flag is set and the conversion command will be known by that or I can wait for this much amount of time and then also I can read the contents from the register. So, the conversion takes the total of S H A time; S H A time plus conversion time. In this case, this is about 20 micro seconds and this is about 22 micro seconds. So, you will get about 42 micro seconds is needed for the complete conversion, but in actual case, we need more than this 42 micro seconds. In actual case, we need to configure the channels, configure the configuration of channels that is channel selection, and then input output selection and so on.

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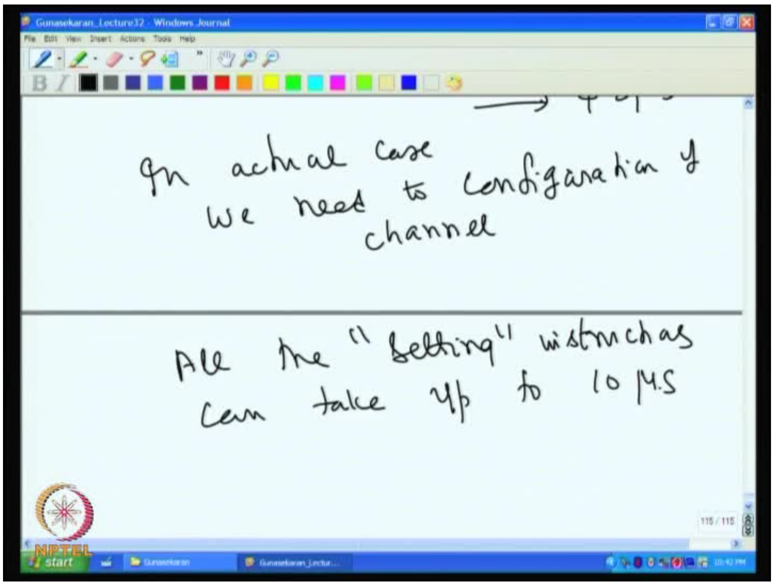

There are various other instructions to be executed which runs up to ten instructions. So, all put together, you may end around 52 micro seconds. So, all the other instructions can take, all the setting instructions can take up to 10 micro seconds. So, one conversion typically needs about 50 micro second time and then only it is possible. It is the minimum time that is required for the complete 10 bit accuracy.

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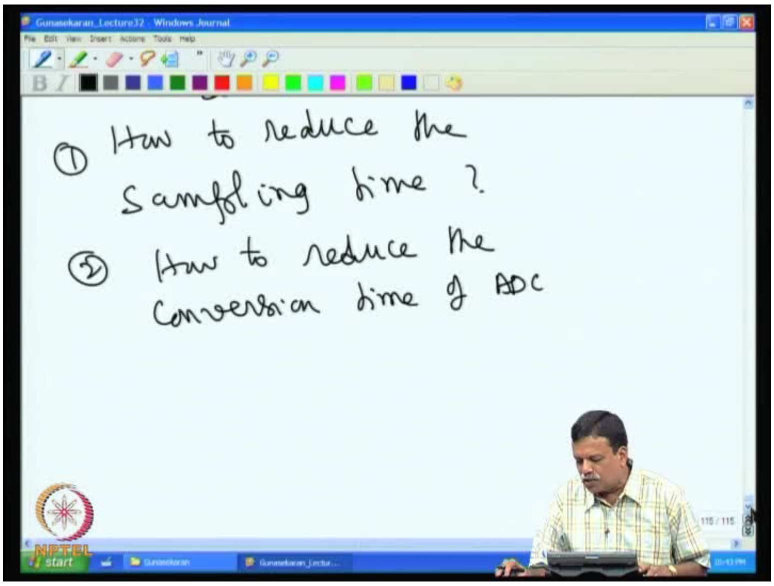

So, the sample and hold amplifier is really a time consuming process because if the sampling time is small, we can considerably reduce the conversion time. Now, there are various techniques that is used in ADC to reduce the time. Let us see how to reduce the sampling time. How to reduce the sampling time?

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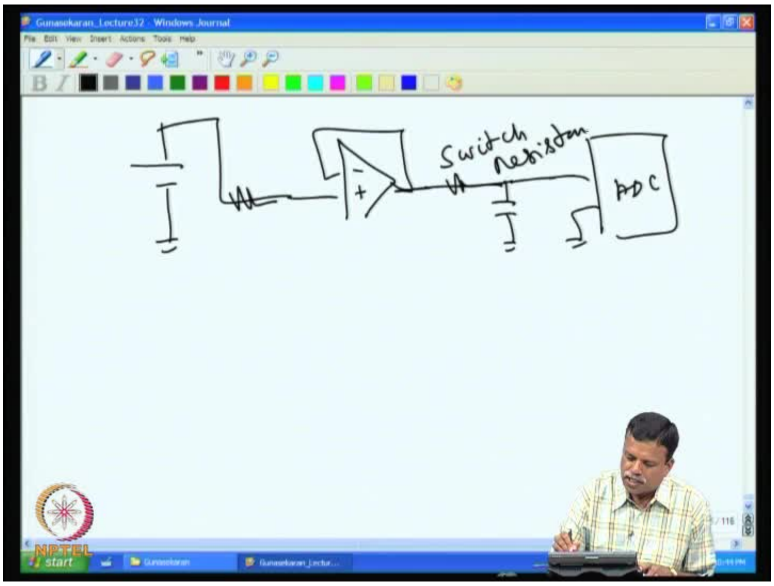

Similarly, we can also see how to reduce the conversion time of the ADC. Now, sampling time, we can reduce by reducing the input resistance. So, one can for example, if I want to digitize the voltage, now, it is better to give through a voltage follower the input so that the output demands is very small. So, even the source resistance is high, the capacitor can be charged very rapidly. Then only you will have a switch resistance that is coming into play and then this can go through the ADC can be connected here.

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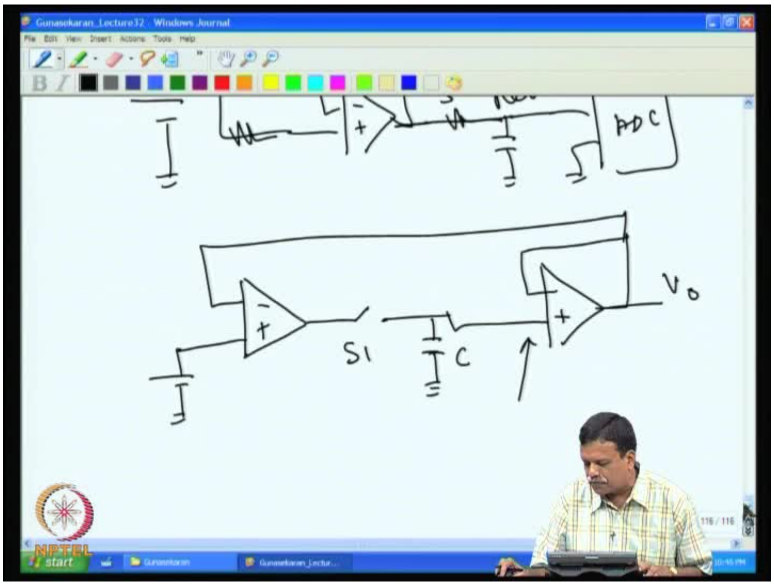

So, if we take this, then you can go through ADC. In this case, the output only switch resistance is coming - switch resistance which can be very small. So, the conversion the charging time can be reduced to few micro seconds. In fact, there are 2 different types of sample and hold amplifiers commercial available. Now, one such circuit is that you have an input amplifier, there you give a voltage follower this thing and you have a switch, voltage follower amplifier and then you have a sample and hold capacitor that can be given and a follower can be given to this. Then it can also be connected to the input so that the total error is not there and then upon charging 1 can disconnect the switch and then the output can be taken from here. This type of sample and hold amplifier gives a sampling time very low - 1 or 2 micro second is possible to sample the voltage and keep it and the capacitor C and the troop is determined mainly by the bias current of the this amplifier.

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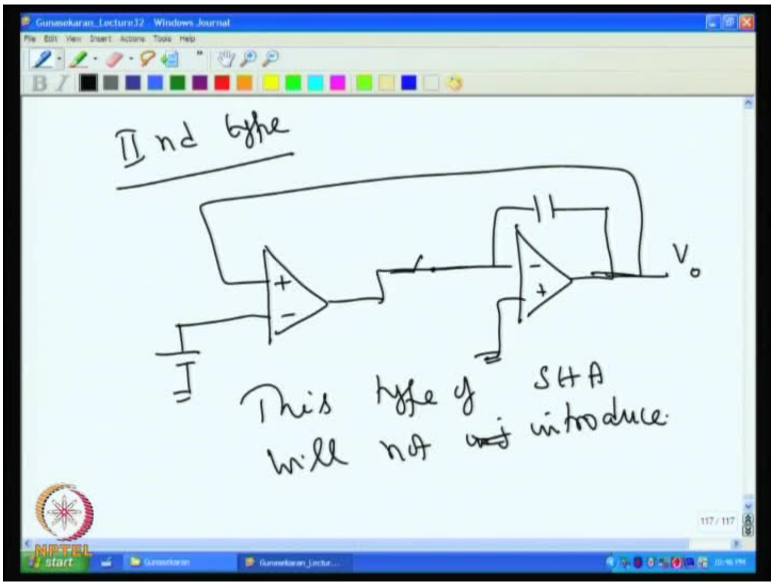

Now, there is another type of sample hold amplifier; that is the second type. What can be done is that you can have an input; input can be given here - input voltage, then you can have a capacitor being charged and this actually, can be given to the process amplifier and the output can come here.

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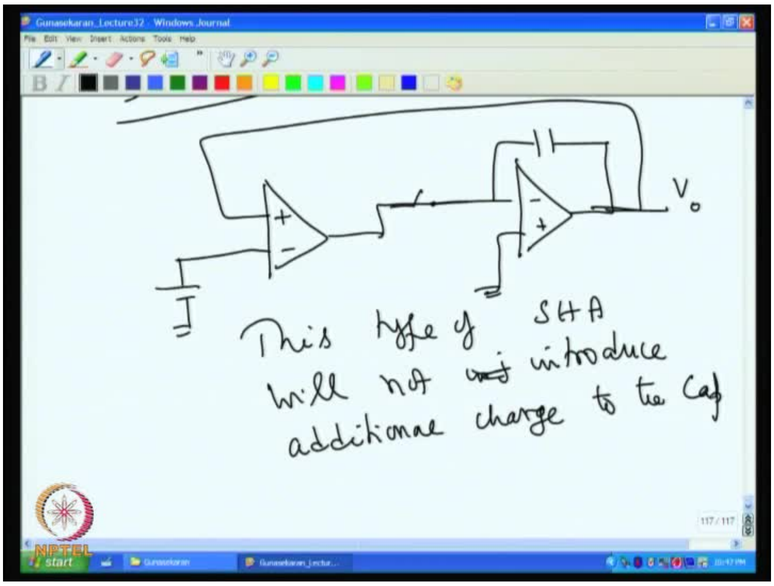

In this case, it is good because that capacitor one, the charging is actually at the ground potential and when you operate the switch for disconnecting the input, the charge injection is very low in this kind of amplifier. So, actually, this type of S H A is popular.

S H A will not induce, will not inject, will not introduce additional charge to the capacitor and this also works extremely well.

But in today’s world, the sample and hold amplifiers are rarely used because the additional overhead plus the time that it takes to charge and the other acceleration problem and so on. People are getting away from the sample hold amplifier and trying to find several other shortcuts to have an accurate conversion.

Now for example, 1 typical case, we can take and then discuss about this in detail. For example, if you want to make for example, solar cell array - street lighting using solar cells. If street lighting system to be designed and if I have to use micro controller and that is A to D controller which is built in micro controller and use this for controlling the street light - solar street light, we will see how this can be done and what are the options that is available to us. So, we take this example and discuss what are the possible things that we can do to reduce the ADC time.

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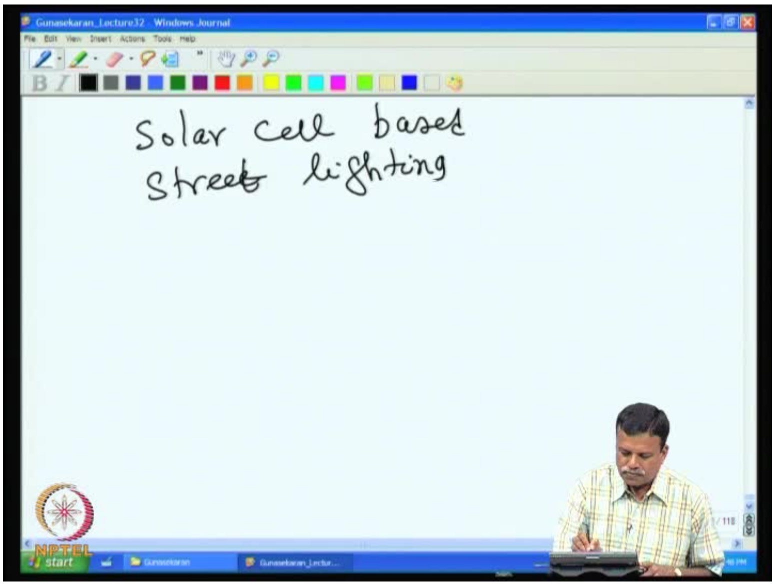

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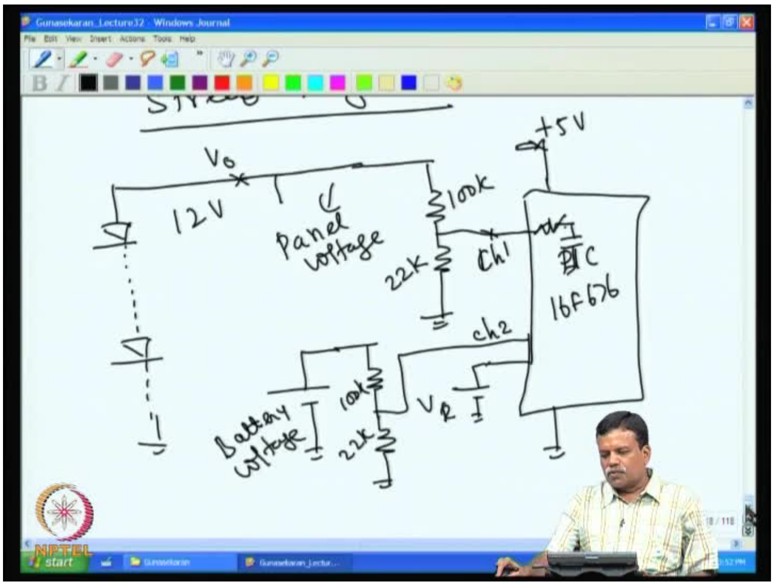

Solar cell based Now, in this case, what we do is we will take a solar panel, for example, we have a solar panel which I show it as a series of diode equivalent circuit, which gives you a voltage here depending upon the intensity of the light that is falling on this and then what is required is we have a battery and then this battery is supposed to be charged. This battery is supposed to be charged whenever the panel voltage is higher than the battery voltage and then we also have to do light switching, actually. That is, if I have a when the voltage is less, that is the voltage is for example, if it is the 12 volt panel, the voltage is lower than 3 volts, we can assume it is already dark and we can switch on the street light.

Similarly, if the voltage is say more than five volts, then we can assume that sufficient light is there and the lamp should go off. So, it is essential that we have to sense the voltage of the panel and voltage of the battery, both are to be sensed using the ADC that is present in the micro controller.

So, in this case, if this is a 12 volt ADC then I will take for example, PIC 16F 676, I use. Then, I give this voltage because the maximum reference voltage that can be given is, if it is 5 volt supply, it gives only 5 volts. So, either I can use the reference for A to D is the inbuilt power supply. it is that say this sorry This 5 volt supply itself can be used as reference voltage or also there is a provision to use V reference external - V reference.

So, what is done is, for example, if you are using a 5 volt reference, which is a power supply reference, then this voltage should not be more than 5 volts because at 5 volts, your output, all 10 bits will be high and beyond that it cannot measure. So, I have to divide this voltage and then give to channel one, for example, channel 1 it is given.

Similarly, the battery voltage also has to be divided and given to channel 2. So, this is a battery voltage; this is a panel voltage - solar panel voltage and the battery voltage are fit to the PIC micro controller for the conversion. Now, if you take this divider, we want very low current actually consumed from the solar panel.

Similarly, battery also should not be discharged because this is all the time connected. So, we want to keep in fact, very high resistance here so that the discharge is very small and also it needs a divider. For example, one possible solution is I can have 100k and then about 22 K. So, one in five, you will get around 2 - 2.4 volts at the input and the same thing can be kept here so that there is not much discharge.

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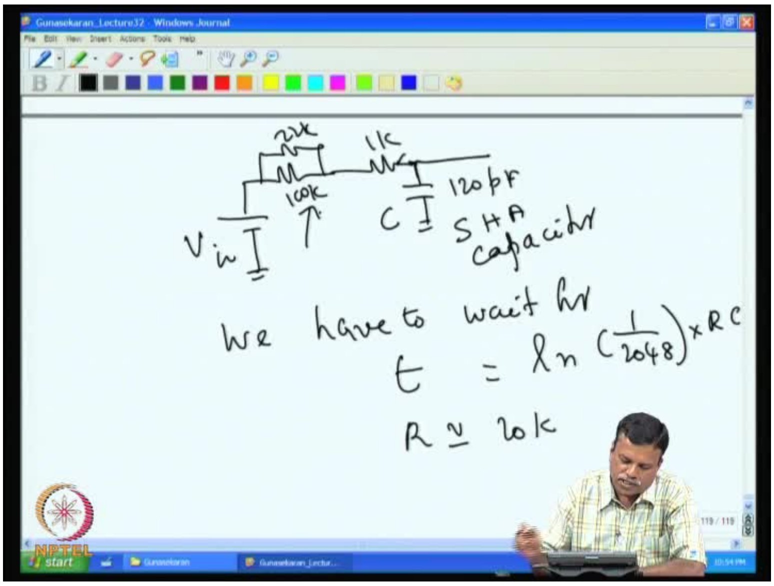

Now, in the circuit, if I see the convertor inside, we have inside about 1 k resistance and then we have a sample and hold capacitor inside. So, if I draw the equivalent circuit of this convertor, it works out to be that I have a voltage source and then the equivalent resistance would be 100k parallel 22k. So, the equivalent resistance would be 100k parallel to 22k and then it has 1k resistance and then you have a switch resistance, which I neglect it, then I have about 120 pF capacitor at the input.

Obviously, this will take about 40 microseconds to reach half LSB of 10 bit convertor because the capacitor the this is actually sample and hold S H A capacitor. So, we have to charge the capacitor to half LSB that is because that is a 10 bit convertor. So, as we discussed, we have to wait for time t that is equal to l n 1 by 2048 into R C. That is C and the R is around 20, this will come around 20k; R is nearly 20k. So, if you see this, you may have to wait almost 40-50 microseconds to reach the half L S B level of close to half L S B of the V input voltage. If V input is 1 volt, then with in half L S B of 1 volt to reach to reach half L S B of 1 volt, we have to wait more than 40 microseconds.

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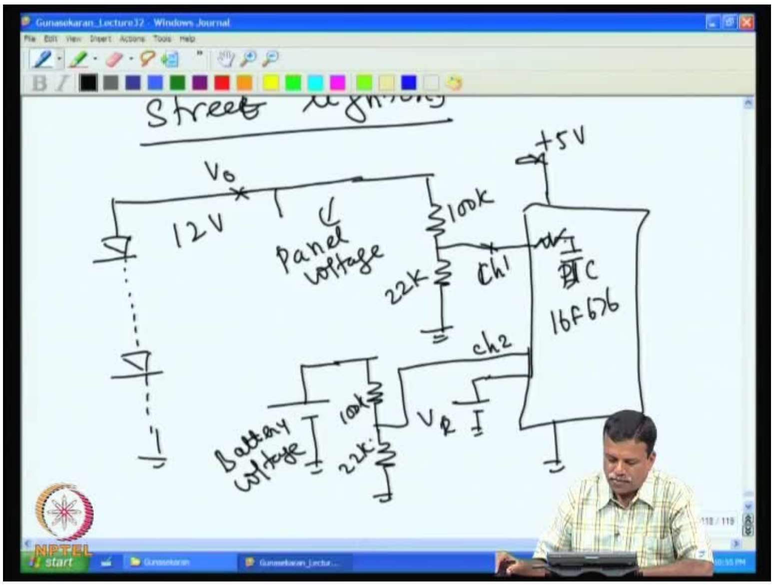

These are quite a long time because this is the main problem because this resistance is higher input resistance, higher because we have opposed to keeping very high resistance here because we do not want loose too much of power here. Similarly, the battery which is already connected, low resistance is used and there will be unnecessarily discharging and by keeping this high resistance, we lost enormous amount of time in sampling the voltage.

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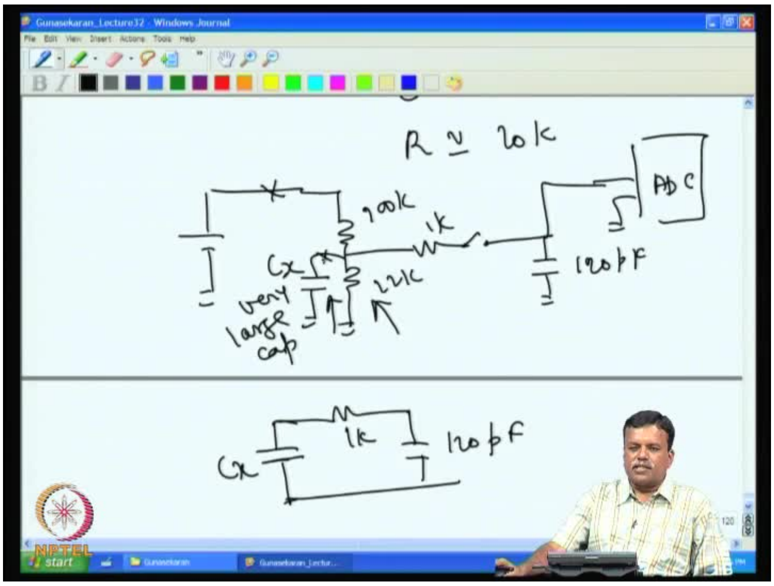

Now, one easiest thing that can be done would be I can introduce an op amp between these two. So, for example, if it is a battery voltage, one simplest possible solution would be have a very large capacitor here and then this can be given to this. So, a very large capacitor say, 1 microfarad, then it goes to the sample capacitor which is the 120pF, then it goes to ADC.

Say, here in this case, 100k and 22k. This is about 1k. Now, this capacitor does not lose much charge during charging. In that case, the voltage drop if it is neglected, then we can ignore these two resistances. The equivalent circuit actually becomes you have a large capacitor connected through 1k to 120pF; this is 120pf and this is 1k and this is C x say, as long as C x is much larger than 120pf, the input is very low and the charging will be done quickly, but problem with this is if the battery voltage changes quickly, then this voltage will not change quickly and then controlling would become very difficult.

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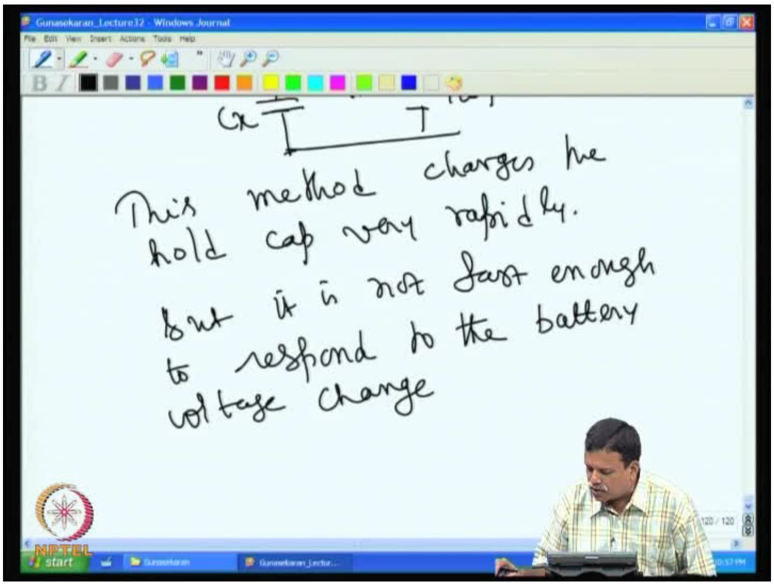

So, this method charges the hold capacitor very fast - charges the hold capacitor very rapidly, but this system is not sensitive enough, fast enough to response for the battery voltage change. It is not fast enough to respond to the battery voltage change.

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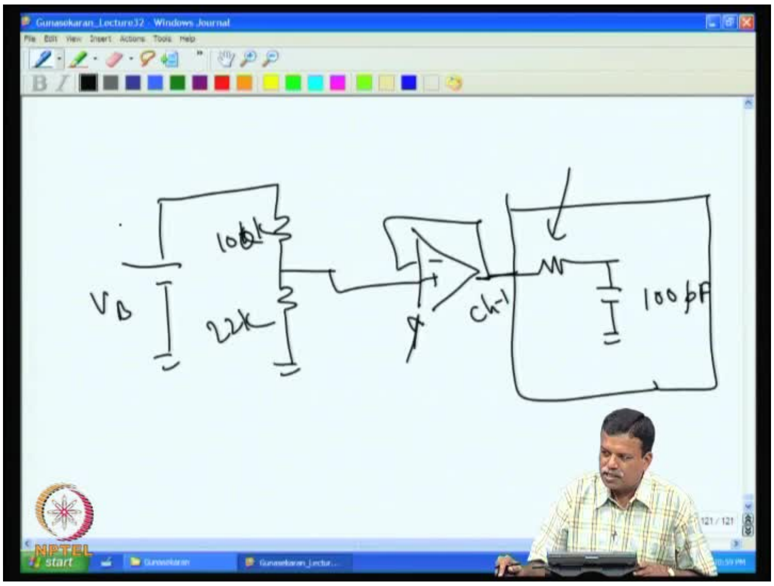

So the this If you want very fast change, then we can use a voltage follower and then reduce the charging time. So, the battery voltage, whatever we have, we can have this 100k and 10k, 100k and 22k, then we can have a voltage follower, reduce the impedance and this can be given to sample and hold. So, this is a 100pF. This actually goes to pick channel one.

So, channel 1 is given to this. The voltage follower gives a very low output impedance and preserves the voltage and this works extremely well and reduces the charging time enormously low. So, practically, this is one of the possible ways of reducing the hold time. Of course, the 1k resistance which is present still creates a problem because there is no easy way to reduce that because this resistance is not in our hand. So, minimum resistance comes in and then minimum charging time to be followed and nothing can be done about it unless we make our own ADC.

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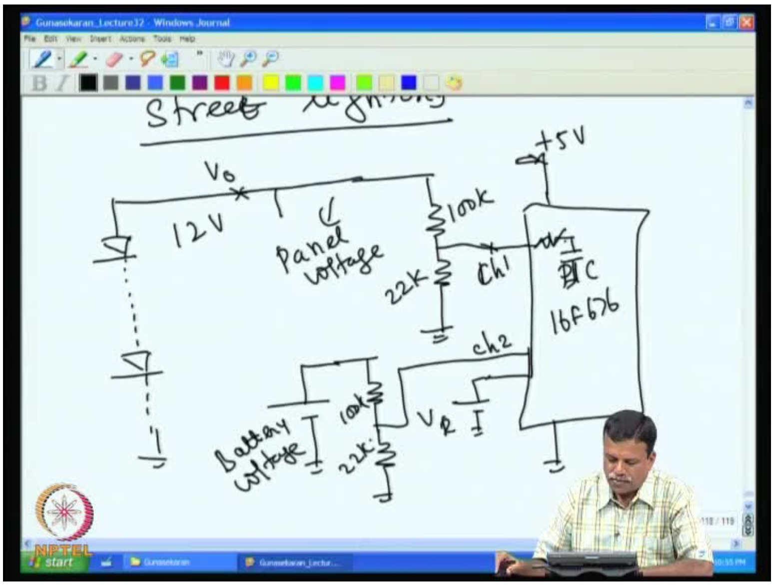

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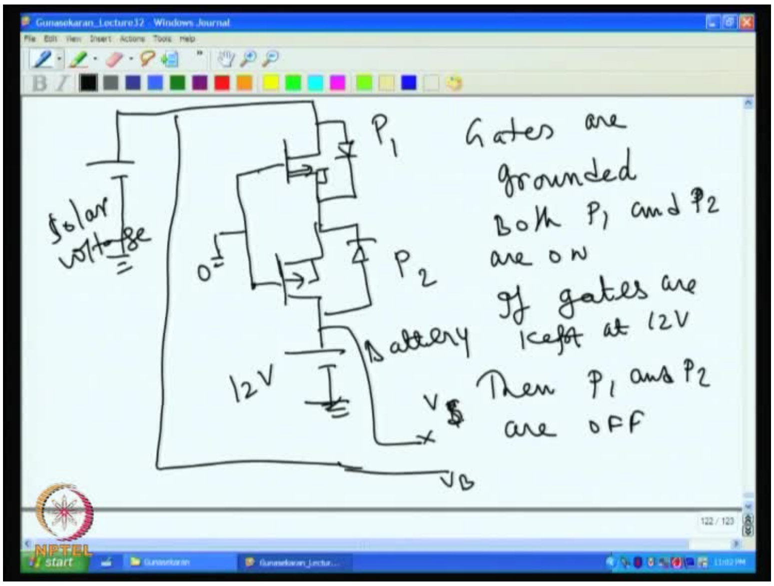

So, this is a V battery voltage. For example, in this case one can measure these voltages - for a battery voltages and the battery voltage and the panel voltage and then they can do the conversion very rapidly. In this case, conversion has to be very rapid. Unless conversion is very rapid, we will get into problem. in this case because For example, when we are charging the battery, we use this kind of circuit. For example, if we are charging the battery, this is the panel voltage - solar voltage. Then if you are charging, normally, what is done is that we will have our MOSFET connected like this, then we put normally the two and this side we connect to the battery and then these two are connected - two gates are connected here. If I want to charge the battery, I will switch on, I will keep this one 0 and then that this has a diode body diode is there and then we have this.

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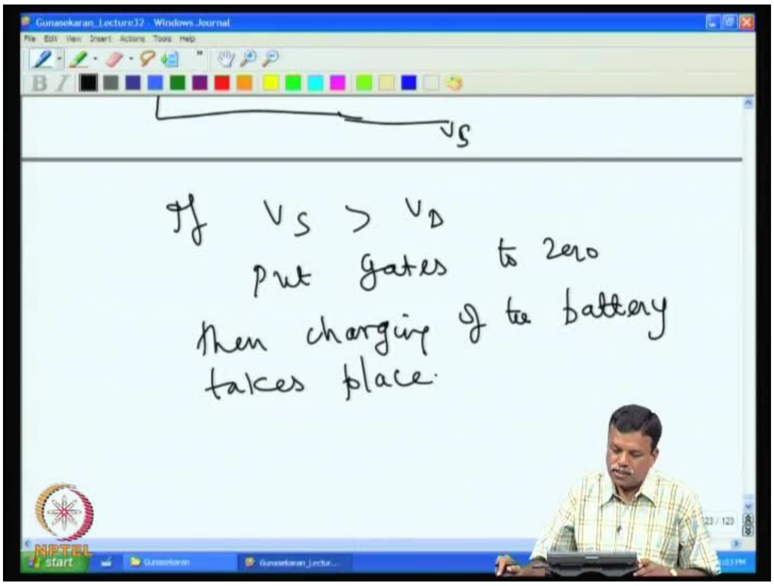

So, when this is connected to 0, for example, if gates are kept at 0, this is a battery; this is solar panel. For example, if it is a 12 volts battery, if gates are grounded, gates are grounded then this is actually p channel MOSFET, this is a p channel MOSFET. So, when the gate is 0 and this voltage is high, then this gets on.

The same thing happens. This is actually 12 volts and this is 0, both the MOSFETs will be on; that is, both P 1 and P 2 both p 1 and p 2 are on. Similarly, if I give the gate 12 volts, if gates are kept at 12 volts, then P 1 and P 2 are off. so we if you Normally, what we do is we will sense. So, through ADC, this voltage as we discussed, this voltage and this voltage are actually sensed say V p and V battery, V solar, V S and V B are sensed and then once V S is greater than this is V. I will put it as V battery is here - V battery, V solar.

So, if V solar is greater than V B, switch on the keep the gates 0 - put the gates to 0. Then charging of the battery takes place. then charging of the battery takes place

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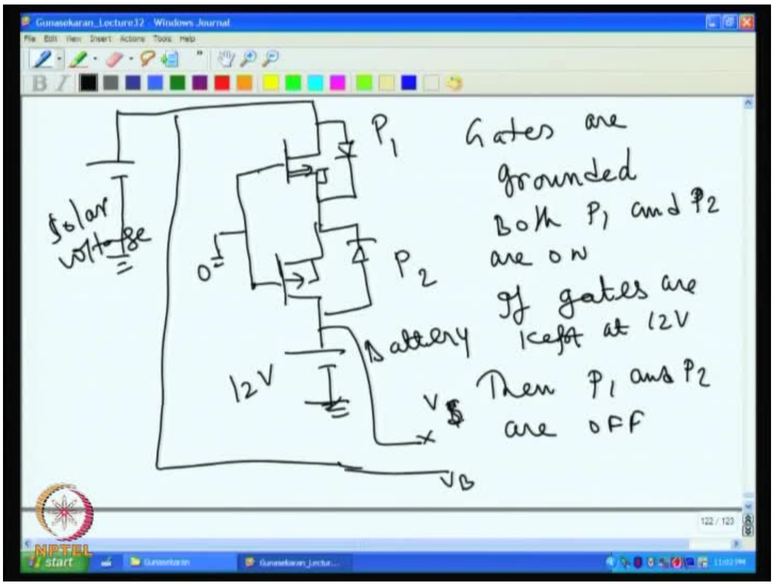

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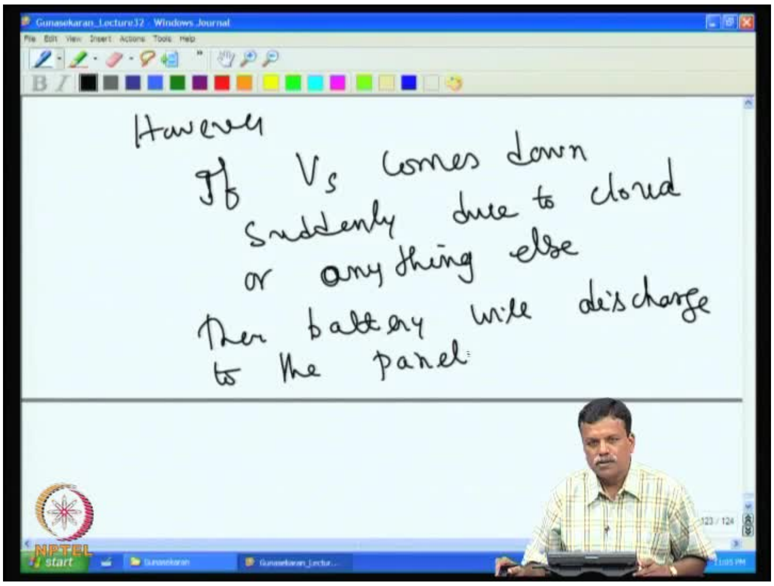

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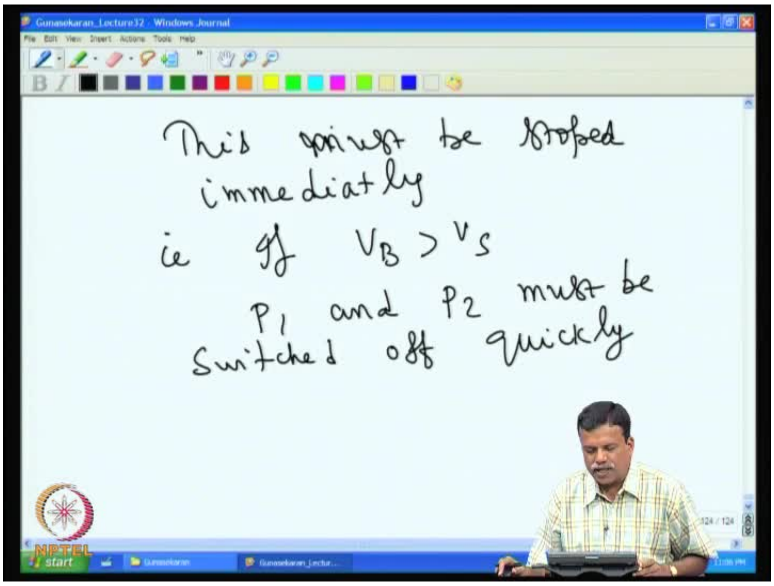

Now, as long as the panel voltage is higher than the battery voltage, there is no problem and charging takes place. In case because of sun going off, if the solar voltage comes down, then battery will discharge to the panel and the battery will get to in and panel also will get spoilt. However, if V S comes down suddenly due to cloud or anything else, anything else then it is required anything else then battery will discharge to the panel, battery will discharge to the panel. This will damage the This must be stopped. This must be stopped immediately. That means one has to continuously monitor the battery voltage and the panel voltage and within few microseconds in case, if the panel voltage is lower than the battery voltage, the switch to be gates to be kept high - that is P 1, P 2 must be switched off.

So, that means, one has to sense very quickly. That is if V battery is greater than V S, P 1 and P 2 must be switched off immediately, must be switched off quickly. So, it is essential that one thus the conversion very one measures the voltage of the panel and the battery very rapidly and takes the decision and then switch it off at once.

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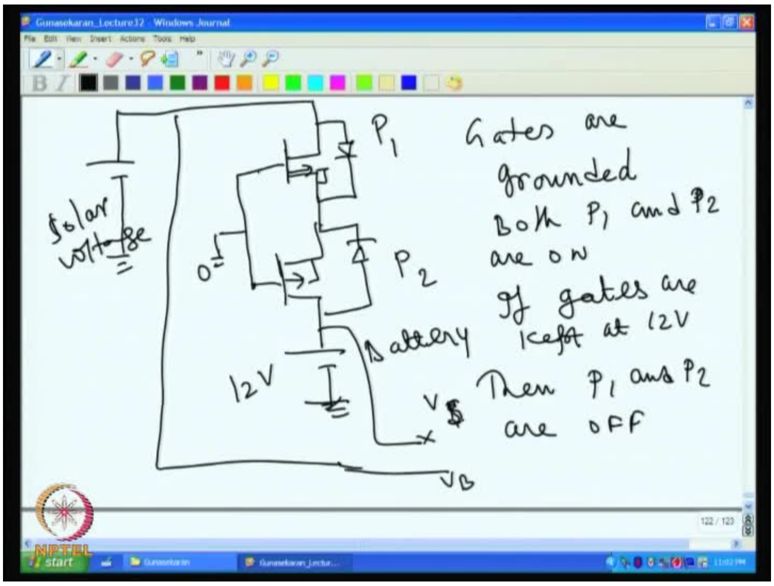

In fact, in real life, what they do is once a battery is once S 1 once P 1 and P 2 are on, once p 1 and p 2 are on, the panel voltage actually started charging the battery. While charging, the resistance across this and resistance across this is a resistance across this. For example, if we take the resistance across this is, it is small - a few milliohms and this is also few milliohms and if the charging current is one ampere, you will have a difference of only 40-50 millivolts between panel and the battery because solar cell has a characteristic, as you draw more and more current, the voltage decreases.

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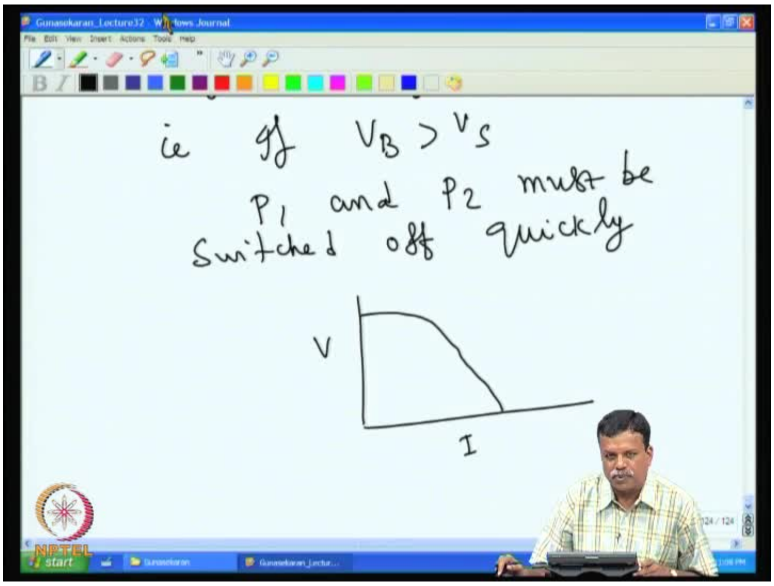

For example, if you take one single cell, the voltage characteristic will be like this. If I take voltage versus current then I will get a curve like this. So, as it draws more current, the voltage decreases. So, essentially once you switch on the P 1 and P 2 voltage, the panel comes down. Of course, as long as sun light is there, the panel voltage will be higher and suppose, if the sun light comes down, then the battery may discharge into the panel, if it is not switched off quickly and in addition, if these 2 voltages are since battery voltage and panel voltage are very close, it is not easy to derive accurately and find out when the solar voltage will go high or low.

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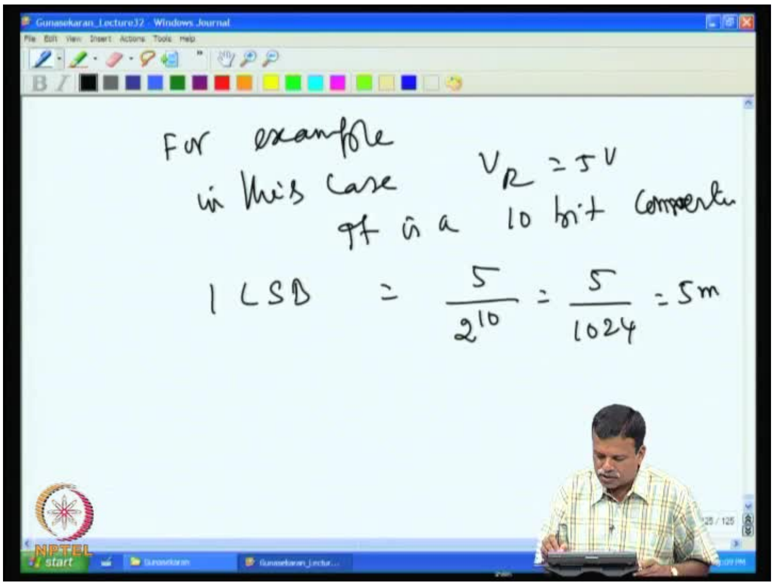

Because For example, in the ten bit convertor 1 L S B value would be can be calculated in the following manner. For example, in this case V reference is equal to 5 volts. It is a 10 bit convertor; it is a 10 bit convertor. So, 1 L S B would be 5 volts divided by 2 power 10; that will be 5 volts divided by 1024; that will be 5 millivolts; that 5 millivolts at the input of the that is, 1 L S B it is equal to 5 millivolts at the input of the micro controller.

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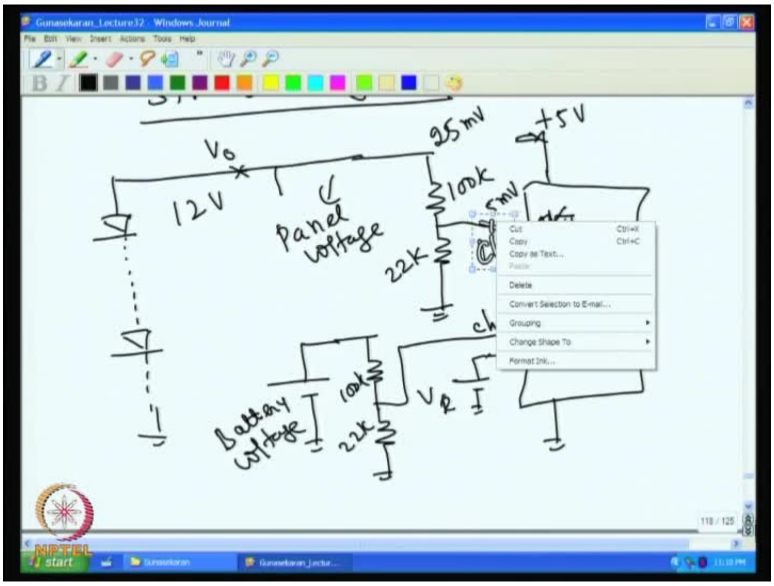

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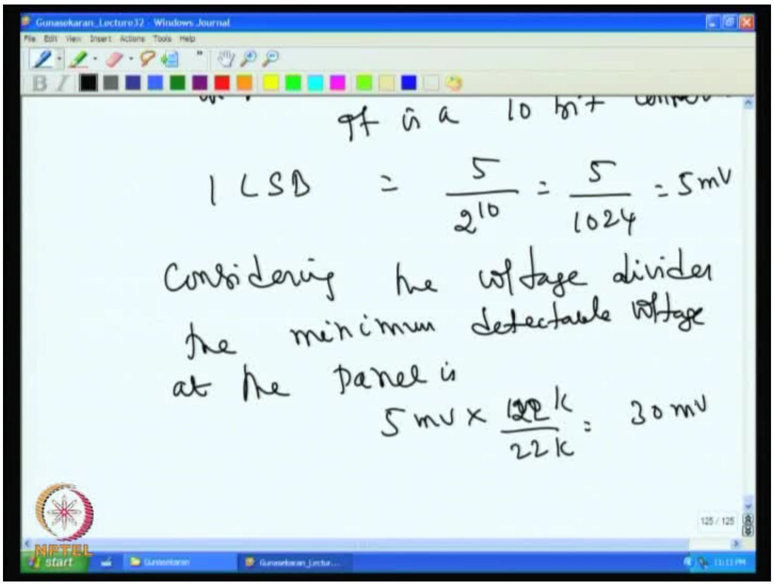

But then we have fed the voltage to the micro controller through a divider arrangement which is 100k and 22k. We have fed the voltage to the panel through this resistance arrangement. So, the resolution at this point is 5 millvolts. So, we have a factor of 5 here. So, this voltage is actually about 25 millvolts; that is, 5 millivolts here, you need of 25 millivolts; that means, the ADC cannot deduct less than 25 millivolts change in this case. That means, the minimum deductible voltage at the panel is 25 millivolts. Considering the voltage divider, the minimum deductible voltage at the panel is 5 millivolts into roughly that is 100k by 122k by 22k; that is, actually, roughly thirty millivolts.

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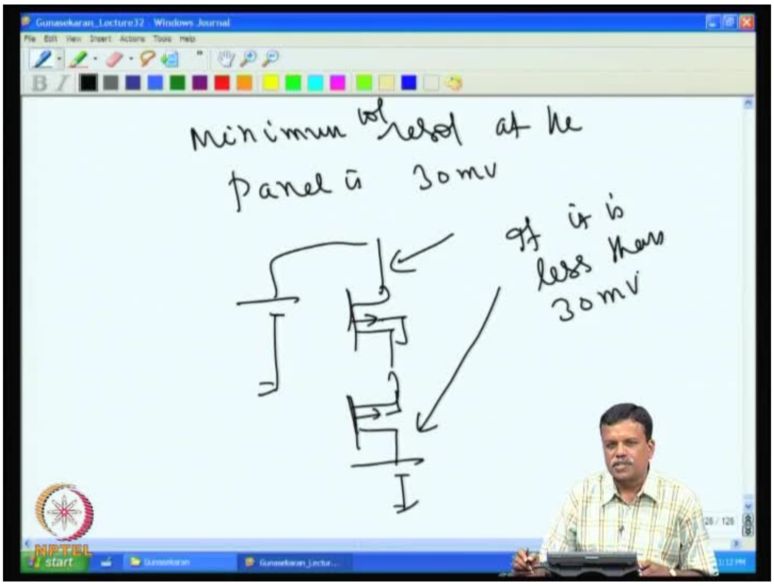

So, below thirty millivolts it cannot be The minimum resolution at the panel voltage measurement is above 30 millivolts.

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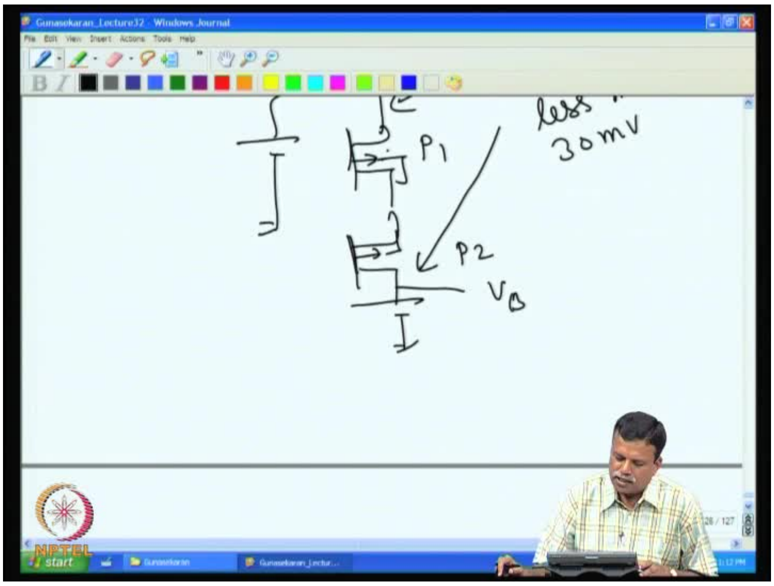

So, minimum voltage resolution at the panel is 30 millivolts. Sometimes, if the charging current is small, then you would not get 30 millivolts difference between the battery and the panel because we have the 2 switches; the on resistance of the 2 switches which are actually very small.

So we have the on resistance of the This is the battery and then the panel. So, the voltage difference between this point and then the battery, if it is less than 30 millivolts, the difference cannot be deducted. So, to avoid this complication, what normally they do is that they will switch off the P 1 and P 2. In actual case, they switch off the P 1 and P 2 for a fraction of a second and then measure the V panel and then V solar and then V battery because when it is off, then obviously the voltage will be higher. It will be correctly known, whether it is lower than the battery voltage because battery voltage is also known here and we are measuring, when it is off.

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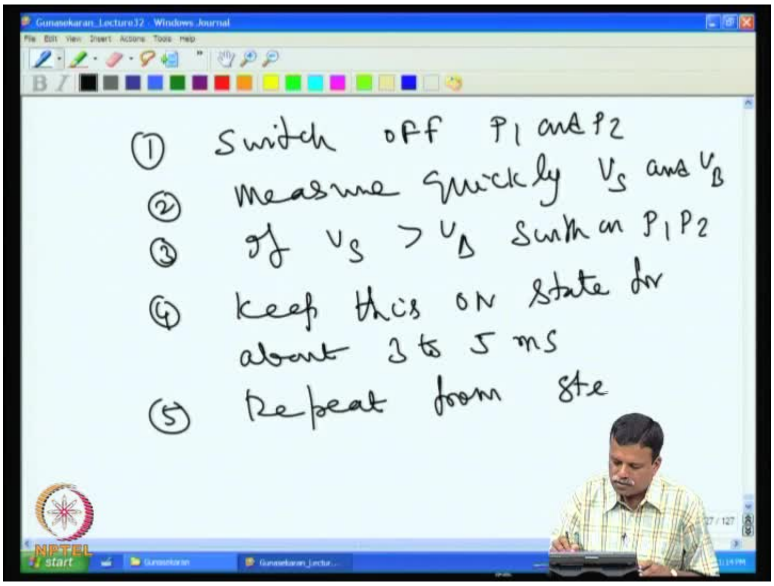

So, if the battery if the solar cell voltage is more than the battery voltage only, you will switch off. So, to deduct accurately, P 1 and P 2 are switched off. Then V B and V B are measured V the V The solar voltage and the battery voltage are measured and then the decision is made to switch on the battery. Normally, what is done is switch off P 1 and P 2, then measure quickly V S and V B. If V S is greater than V B, switch on P 1 and P 2. Keep this on state for about 3 to 5 milliseconds and then repeat from step 1.

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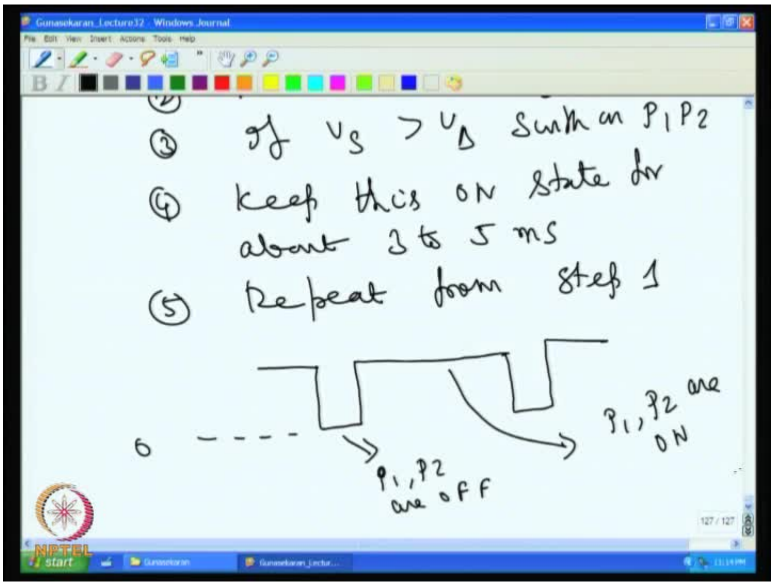

So, what is normally done is that you switch off. That is, if I show graphically, you switch off for some time, then switch on this, then go like this. So, here actually during this time, this is 0; P 1, P 2 are off.

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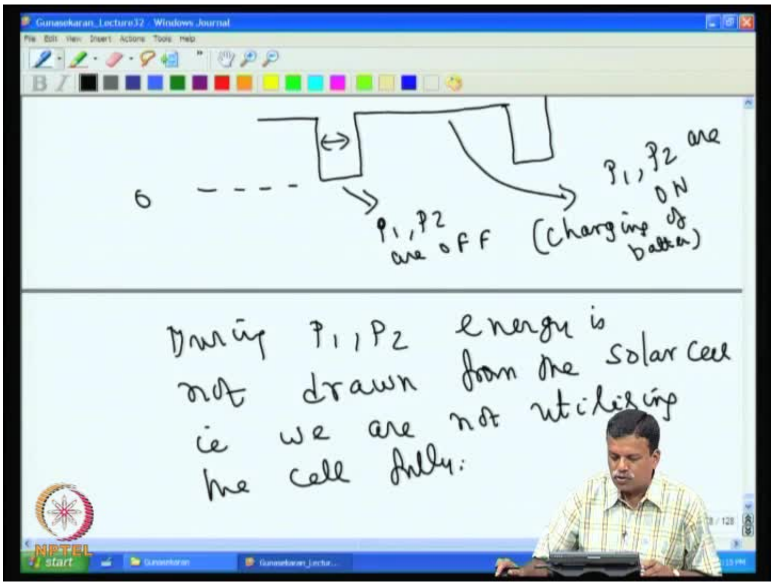

Here P 1, P 2 are on. That is charging. In this case, charging is taking place - charging of battery. So, this time is really the conversion time. That is because during this time, when the P 1, P 2 are off, no charging is taking place from the panel. It is a waste. So, during P 1, P 2 energy is not drawn from the solar cell; that is, we are not utilizing the cell fully.

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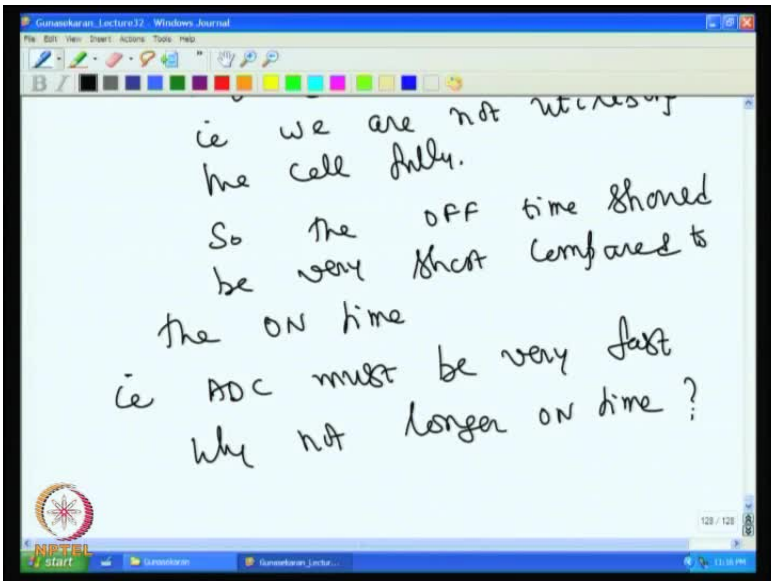

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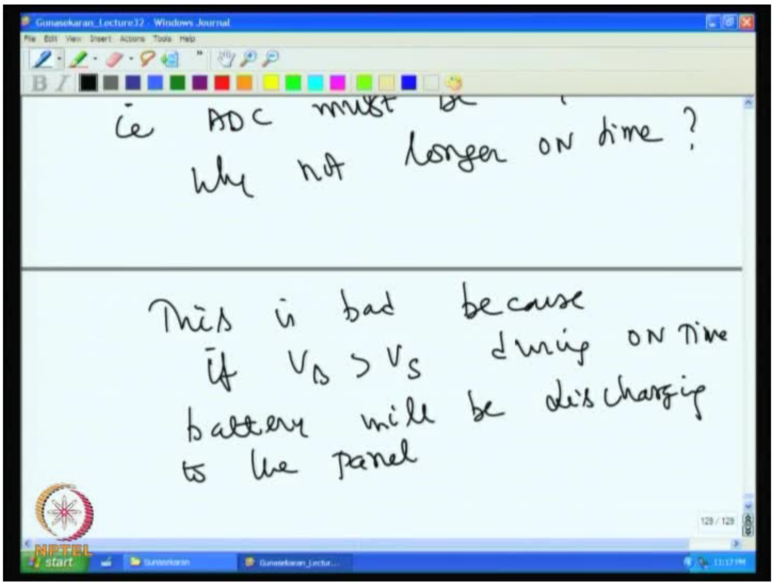

So, P 1 and P 2 should be as short as possible. So, the off time should be very short compared to on time. That is why the ADC must be very fast; that is, ADC must be very fast. One may ask why not we keep longer on time. Why not longer on time? Longer on time can create a problem because if the sun light goes very rapidly, the voltage drops then battery will be discharging for longer time. So, we should not give longer on time. This is bad because if V B is greater than V solar cell and during on time, battery will be discharging, battery will be discharging to the panel.

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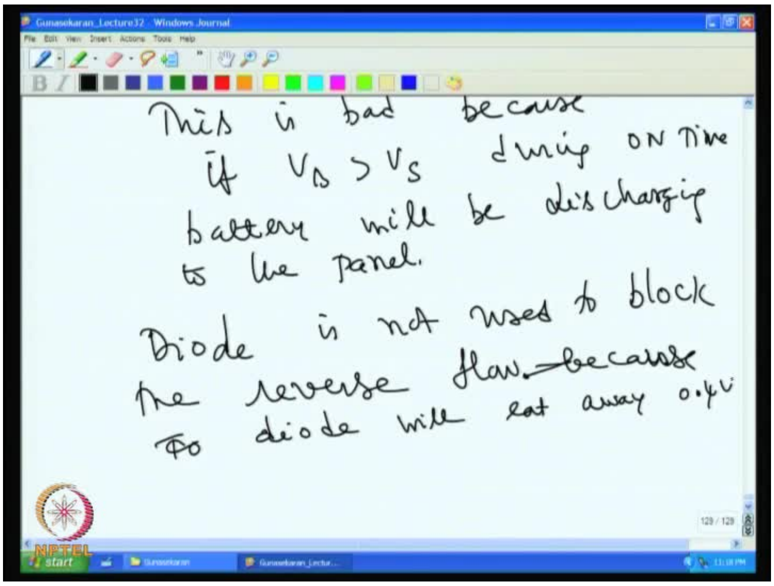

So, to avoid that only, it is done. We may ask why not use a diode and then do one way charging only, but then diode will eat away 0.6 volt. That is why diode is not used; diode is not used to block the reverse flow. Diode is not used to block the reverse flow to avoid reverse flow because diode will eat away 0.6 volt or 0.4 volt, even if you use schottky diode.

So, to avoid this only, this technique is done. In this case, we need to have very fast conversion time. Then only, it is possible to utilize the solar panel for the fullest extent. So, like this we can have many examples. Why we need a fast conversion and then how one can achieve a fast conversion by reducing the sample and hold time and then try to get to higher fast fastest convertor for our work.

There are faster convertor techniques like for example, we have flash ADC convertors and that is much faster than successive ADC, which we have discussed. We will see about this flash ADC convertor and so on in the next lecture.

Thank you.