High Power Multilevel Converters – Analysis, Design and Operational Issues

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Lecture – 40
Gate Driver Circuits - Features of Gate Drivers and Basics of Bootstrap Functionality

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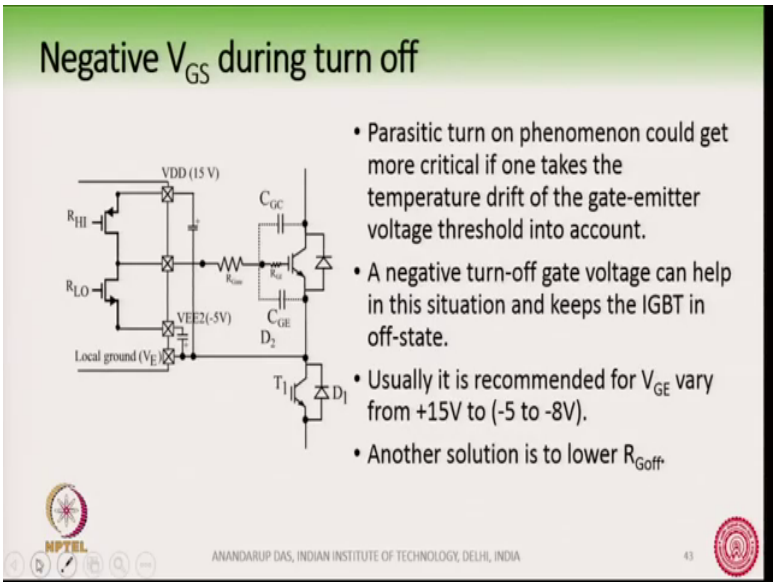

Now, you will appreciate, why we had made V GS negative.

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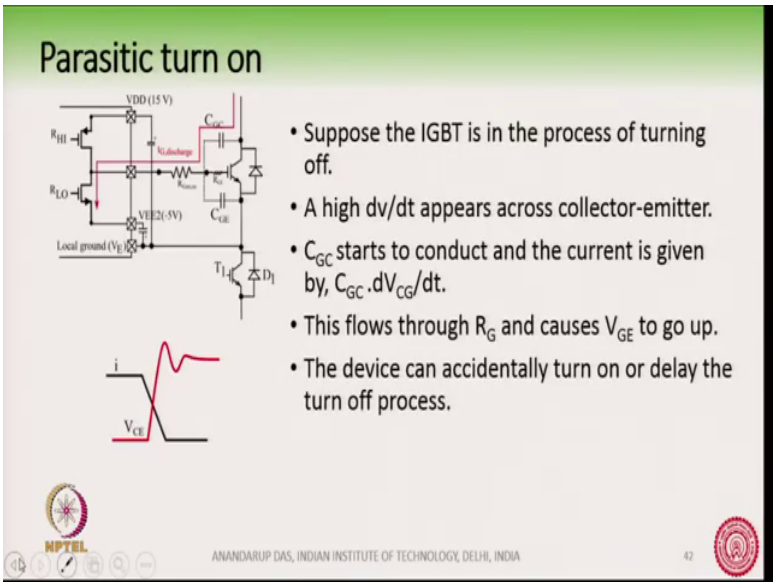

So, another solution to take care of this parasitic turn on phenomena, one more solution is to make V GS negative right. So, why? If you make V GS negative, that means this voltage if you try to go into this one. If you try to go into minus 5 volt, then in spite of this happening in spite of this happening this points potential ok.

In spite of this current flowing here and there is a potential increase here. The gate emitter voltage that voltage will not cause a spurious turn on of the device ok, due to some unforeseen circumstances. So, because the V GE voltage has been V GE voltage has been kept to minus 5 volt ok. So, therefore the V GE voltage is generally varying from plus 15 volt to minus 5 or minus 8 volt ok.

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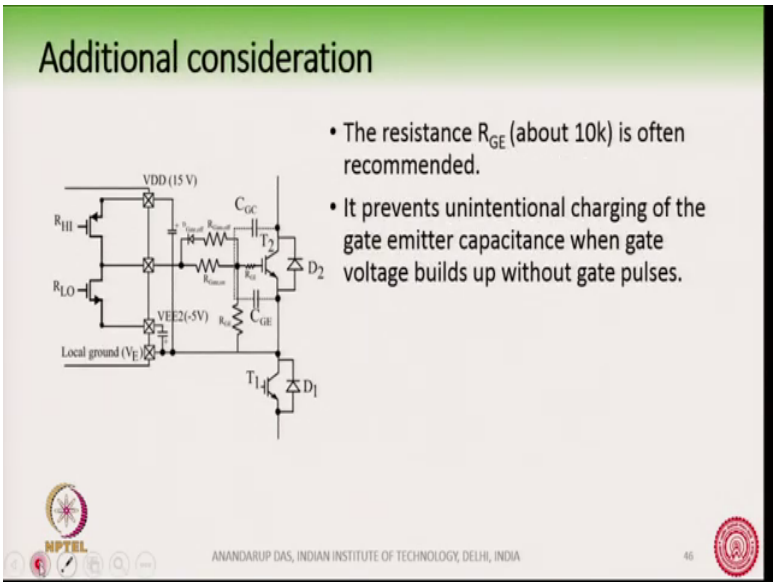

Some another consideration that you should keep in mind, is that this R GE. So, often if you keep the IGBT like floating the gate potential to be floating. Then it is not a good idea to keep the gate potential floating ok. Because it can cause unintentional charging of the gate emitter capacitance ok. It will build up, this gate emitter capacitance a gate emitter voltage will build up without even the gate pulses ok. So, it is always a good idea in particular for high power applications, that this gate terminal is connected through a resistance R GE typically about 10 k ok.

So, that this this point is not floating ok. So, this was some of the these were some of the considerations, which we should keep in mind while designing the gate driver gate driver resistance and other resistances which we have discussed. Another thing is the power to the

gate driver board. Often like in multi-level converters gate driver boards are not separately powered from an external source ok.

They are powered from the DC link itself ok. So, there is no separate power supply for the gate driver board. So, if you see the MMC or cascaded h bridge cells, the cells have this DC link and these DC links are these DC links are connected to the h bridge IGBT for example. When the DC link is available? Then we take the power of the gate drive board from that high voltage DC link itself. For example, if it is 1000 volt we can use a fly back converter to get a 15 volt supply from that 1000 volt DC link and power hour power the gate drive board, this is often done ok.

So, there is no power separate power supply to the gate driver board it is done because of isolation. Because we would like to keep the gate driver board completely isolated.

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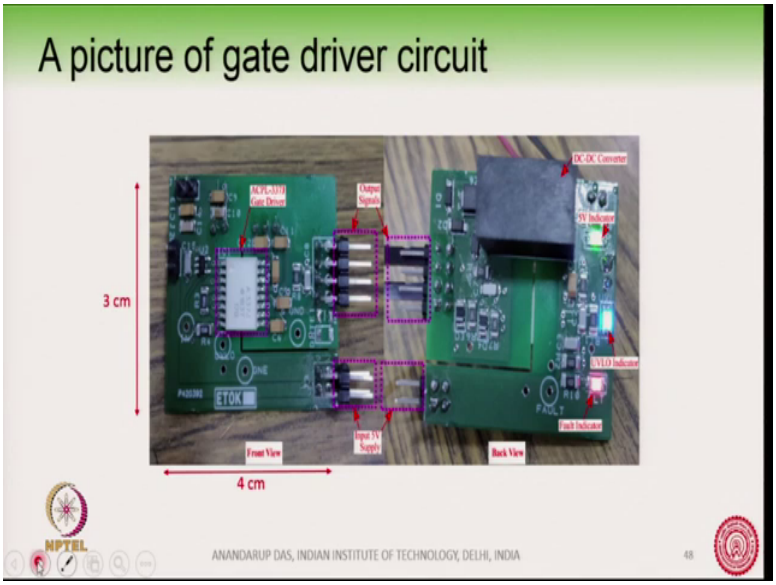

So, see this you can see one such gate driver board of course, this is not a commercially made. But we have made it in the lab we just put a picture just to give you an idea that how small this gate driver board actually is ok, its quite small. And here we have used a gate driver IC ACPL337 from Broadcom. And so, you can see this is only 3 by 4 centimetre. Even this is not very optimum you can make the gate driver board even smaller.

So, this gate driver board has many protection features as also this driver IC also provides us with that. So, it is also has an isolation of the DC-DC converter and there is also a cut on the PCB, so as to provide a physical isolation. And so we have been using this gate driver board to drive the sick MOSFETs, but it can also be used for driving IGBTs or silicon MOSFETs.

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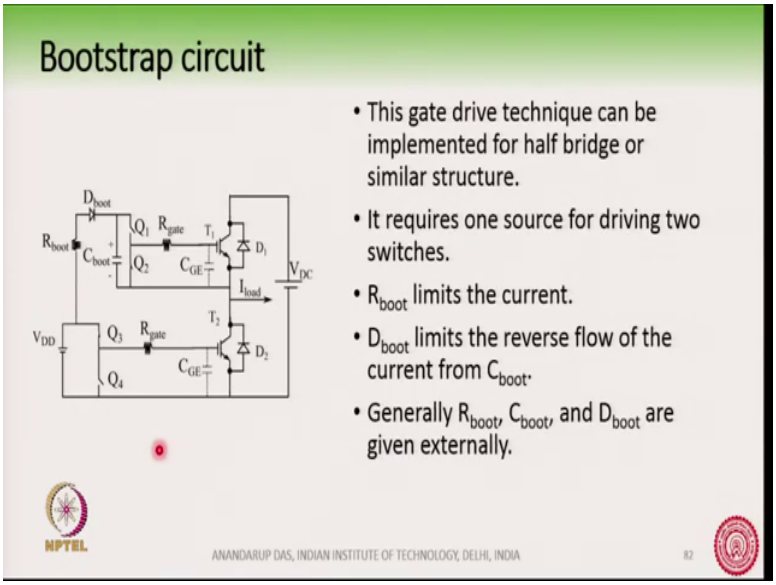

So, now we will talk about bootstrap circuits ok. Now often we see that we will drive for example, for this kind of voltage source converter we often drive half bridges. And we have

seen that we can use gate driver boards for each IGBTs upper one high side IGBT one driver, low side IGBT another driver.

Now, of course the question comes up that can we use a single driver for both the devices and there comes the advantage of a bootstrap circuit? Ok, with a bootstrap circuit, with one single driver or gate driver we can drive both the upper and lower side IGBTs for this we will need some additional components ok which we will see here ok. But with one source as you can see here with one source V DD we will be driving both the upper and lower side IGBTs fine.

So, in this bootstrap circuit what are the components? So, you can see here this is the power side here ok. And you have the capacitances you can also have the capacitances, the gate collector capacitance is not shown here. And then you have this voltage source a single voltage source. And then you have also 2 transistors here Q 1, Q 2 sorry 4 transistors Q 1, Q 2 and Q 3, Q 4 and some other elements like R gate, D boot, R boot and C boot ok.

So, the bootstrap basically requires this R boot, D boot and C boot externally. Because nowadays, the gate driver ICs they come along with this bootstrap functionality ok. So, this Q 1, Q 2, Q 3, Q 4 is also part of the gate driver circuit, its inside the IC ok. So, what you have to give from externally is this R boot, D boot and C boot these resistance diode and the capacitance these three elements. And along with that if you want if you can have this R gate also ok, externally you can give. Many ICs are coming up with this Q 1, Q 2, Q 3, Q 4 already given to you ok.

So, let us first see how this circuit operates?

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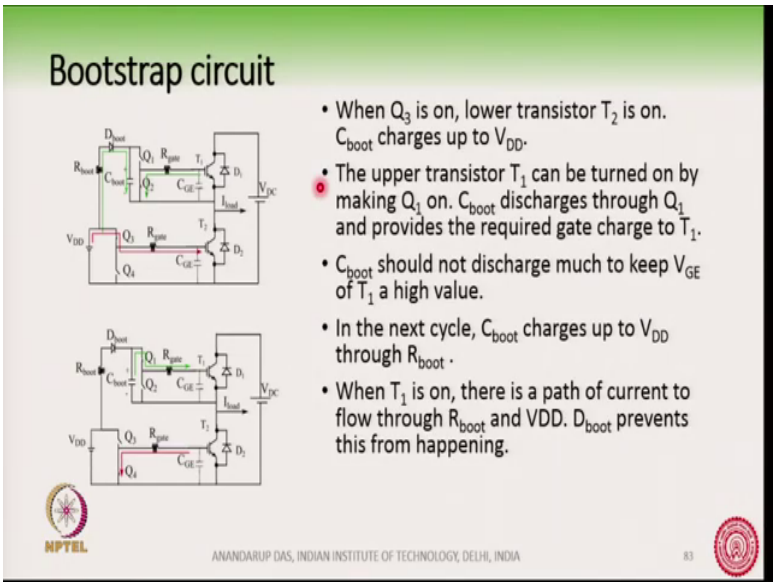

Now, suppose in this let us see this circuit and I am turning on this transistor lower transistor this lower IGBT here T 2, I am turning on T 2. In order to turn on T 2, I will turn on Q 3. So, you have a VDD voltage and the current will flow like this and will complete the path like this ok, the current will complete the path.

So, after turning on Q 3 this voltage will give the charge required to turn on this lower IGBT. Now suppose I want to turn on the upper IGBT ok. So, the upper IGBT can be turned on by turning on Q 1 ok. So, I will ok so, I will turn on Q 1 and of course, when I am turning on this transistor T 1 that IGBT T 1, I will turn off T 2. How can I turn off T 2? I will turn on Q 4 so, it can be discharged like this here. So, the lower IGBT operation is pretty simple.

So, let me let me reframe it once more. The lower IGBT operation is pretty simple. With Q 3 and Q 4 you can charge up and discharge this lower IGBT. But what happens with the upper

one? Note that, when you are turning on this lower IGBT by turning on Q 3, if you have turned on this lower IGBT then, there is a path for current to flow ok as shown by this green arrow here. You see from VDD goes like this through R boot, D boot, C boot and like this here ok, there is a path for the current to flow.

So, when the T 2 has been turned on this capacitor C boot will be charged to VDD voltage ok. Now this charge this capacitor C boot, which is charged is now useful for turning on the transistor or the IGBT T 1. How? Now when you want to turn on T 1 what will you do? You will turn on Q 1 and then this C boot will follow like this here, C boot will discharge and will provide the gate charge required for T 1. So, C boot will discharge here.

So, whatever charge the C boot had accumulated, when the lower transistor was lower T 2 was on. Now it is discharging here. But note that, it should not discharge too much because if it discharges too much, then this gate emitter voltage of T 1 will fall and we do not want that to fall. We would like to keep the VGE high so, that the on-state V CE V CE on is a minimum value small value. So, we should therefore choose a value of C boot or the capacitance values should be high. So, that it should not discharge much. So, that the this VGE voltage does not fall.

Again, when I want to, so once again when I want to turn on the load transistor, I will turn on Q 3 and I will turn off Q 1 ok. I will turn off Q 1, and so this IGBT will discharge through Q 2 here. It will discharge through Q 2 and this C boot will charge up through the lower path again like this. So, the cycle so the C boot is again ready for the next cycle ok. So, in this way by using this C boot we will be able to turn on and off both these IGBTs from a single voltage source. So, this is the advantage.

Now of course, why R boot is needed? Because. when the C boot has discharged a lot then, when you are charging this capacitor, if you do not use an R boot there will be a high inrush current. And R boot will prevent that inrush current. Why will you use a D boot here? What is the function of the D boot or the diode? Note that, when T 1 is on when there is this T 1 is on, there can be a current flow from this DC bus through T 1 through this C boot, suppose there

is no diode here. So, the current will flow through this through here and complete the path like that ok, here is the path which I am showing now.

VDC through this T 1, C boot, R boot, VDD like that as soon as you turn on the T 1. So therefore, the D boot is necessary and it prevents this short circuit of the DC bus with the control power supply VDD, and it stops that from happening. So, how can you design this bootstrap? It is very easy actually.

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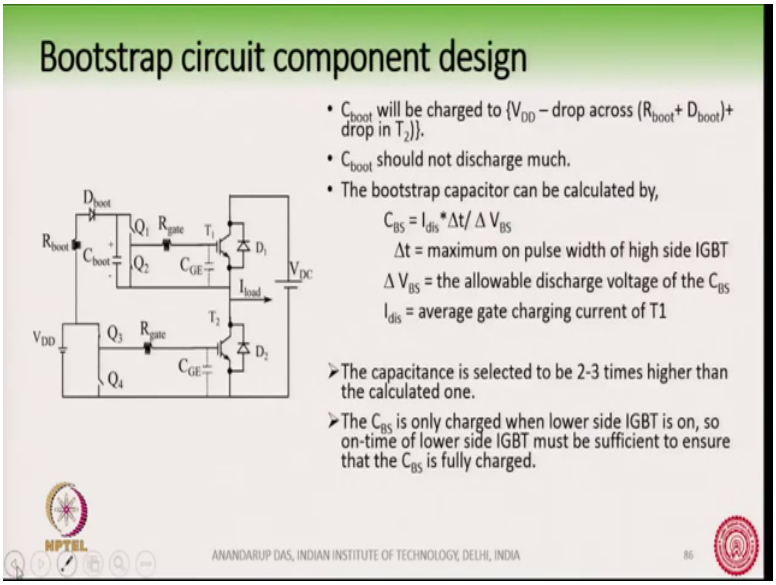

So, because what will you do? You will see C boot, C boot will be charged too, so when the C boot is getting charged up, it will charged to V DD minus the drop across this one and the drop across T 2 ok. So, this much is the voltage to which C boot will charge up. And the C boot should not discharge much, so this bootstrap capacitor can be calculated. So, C bootstrap

or the C boot the value C boot is equal to I discharge times delta t divided by delta V bootstrap ok.

So, because how long it will continue? How long it will discharge? It will discharge the for the maximum on pulse width of the high side IGBT right.

So, the duration for which this transistor is on that is the delta t time and the total discharge average discharge current is I dis. That means this factor here is the total gate charge required by the IGBT T 1. So, this total gate charge of T 1 divided by, how much voltage we will allow to fall in the bootstrap capacitor that is what we will. So, this is the total charge divided by the delta VBS that is the amount of voltage we will allow this to fall. So, that is how you will calculate the bootstrap.

And the capacitance you can select 2 to 3 times higher than this value. So, as to keep it within a safe limit ok. You should also note that the lower side here lower side IGBT should be sufficiently should be turned on for sufficient amount of time. So, that this here will be fully charged up ok. So, this is for the discharging part how much delta V BS? But at the same time this device here should be sufficiently turned on the PWM pulses should be such this should be fully. So that, this capacitor gets the time required to charge it back, to get back its charge from this supply here.

At for many such bootstrap circuits the first pulse should be on this the first pulse should be on the lower IGBT. Because suppose when it is turning on, C boot is fully discharged. So, the first thing before you can really start the converter is to charge this C boot to the V DD value. So, initially you will turn on this device and we will charge this C boot to a certain value then only, you can start your operation of the converter.

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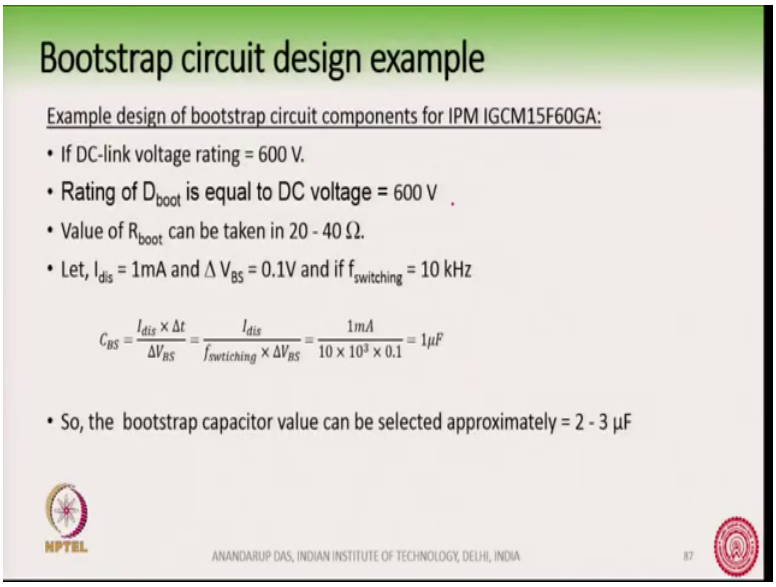

So, I we have taken a very simple example of a bootstrap circuit components for this for this is an IPM we will talk about this IPM. For this IPM IGBT. Suppose the DC link voltage is 600 volts, and the rating of D boot is equal to 600 volts. So, this can be obtained by applying the KVL here ok. If you apply the KVL then you see how much D boot has to block.

So, you can see here for example, this is the path where D boot is operating. So, this is the V DC minus this drop, plus C boot ok. This voltage comes across this terminal whereas, this V DC minus V DD this comes here on this terminal ok, on the anode and the cathode. So, how much it is blocking? You can see that it is blocking this full DC bus voltage.

So, the voltage rating of D boot must be equal to the or more than the DC bus voltage. So, rating of D boot is equal to the or more than the DC bus voltage. And then R boot you can find out yourself that R boot. Because we are doing an RC time constant. So, you can take a

20 to 40 ohm, but you can choose any value. And then you can find out from this how much is the total charge needed? And then we can find out that ok, we have given some example here, for a switching frequency of 10 kilo Hertz, that you need a capacitance of 1 microfarad.

For this particular IGBT, which we have used in the lab so you can take 1 micro farad capacitance. And the bootstrap capacitor value can be selected a little bit more than this maybe 2 to 3 micro farad and this works quite fine.

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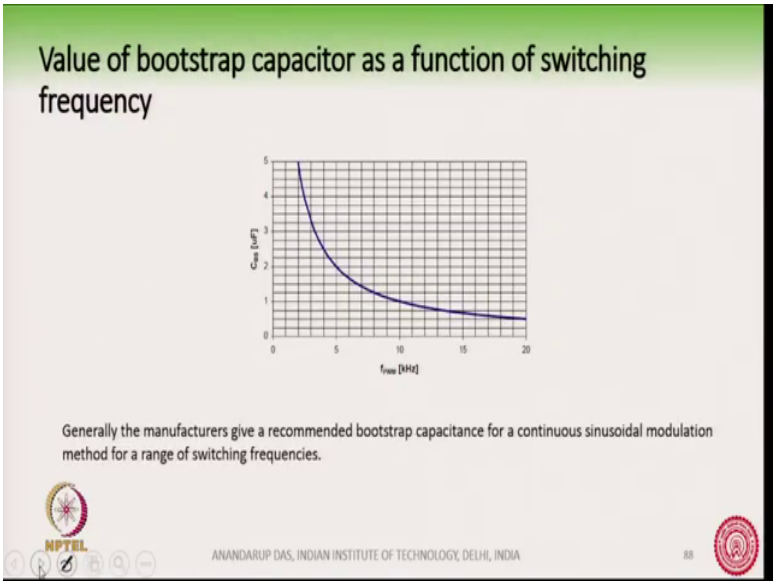

In fact, some of the manufacturers give a recommended bootstrap capacitance in their datasheet even, they will give a recommended bootstrap capacitance depending on how much is the PWM frequency? So, if this is PWM frequency is low. I mean if the PWM frequency is low, then you will need more bootstrap capacitance. Of course that is needed, because then

you will have to hold the voltage for a longer duration of time. So, that is why your capacitance value will increase.

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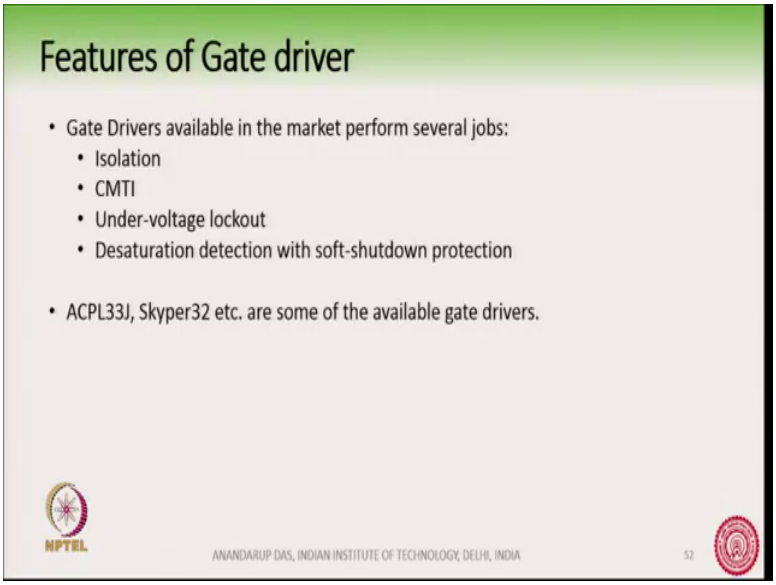

We will see little bit of some of the gate driver functionalities, which are commercially available in the market ok. Gate drivers there are many gate drivers available in the market and obtained from different manufacturers. For example, ACPL33J, Skyper32 these are some of the available gate driver circuit. Almost all manufacturers of devices also have their own gate drivers.

Now, why I included we will talk briefly about say next 10 minutes, about some of the features of these gate drivers. Why we included this is to understand when you purchase some of these ICs gate driver ICs there are certain features, which you should be aware of ok. So, I

included these slides here. You can also make your own gate driver that is that can be very useful and you have a full control and knowledge over that.

However, in many cases the gate driver ICs, which are now available. They are number one very compact and they have they are providing a lot of functionalities. Which for a person who wants to make the whole gate driver on his own? He may find it difficult at times to incorporate all these features within a small IC like this this much. So, the general trend is to use these commercially available, gate driver ICs nowadays.

So, there are 4 or 5 important terms apart from this there are other important features also in the gate driver, but isolation, CMTI, under-voltage lockout, de sat detection these are some of the features of gate driver already available to you.

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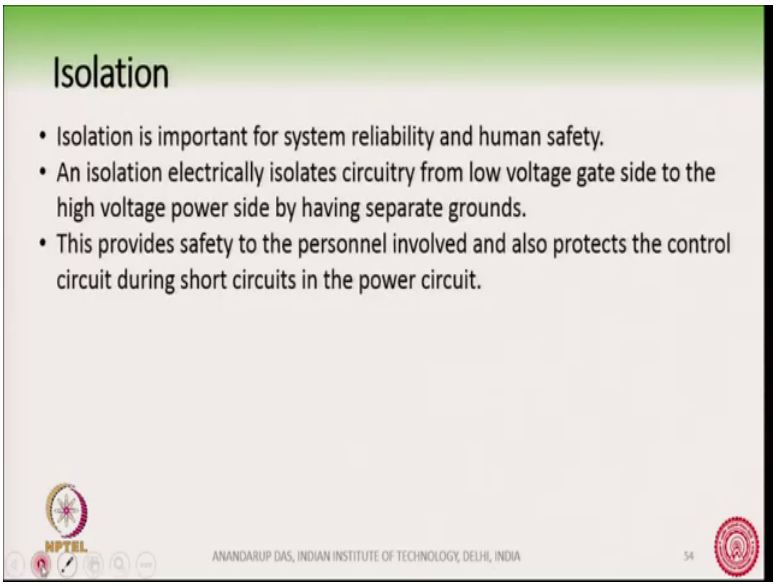

So, what is what are these features? So, we will briefly explain because if you purchase some of these gate driver ICs, you will see these terms and some pins associated with it in the IC. And we should be kind of like a little bit knowledgeable about what does those? What those pins? Or what those mean? So, of course we know that isolation is a very important functionality for a gate driver ok.

So, because it on one side there is a low voltage and the other side is a high voltage. And so we the gate driver basically electrically isolates the low voltage and the high voltage side. It is particularly useful during short circuit in a power circuit.

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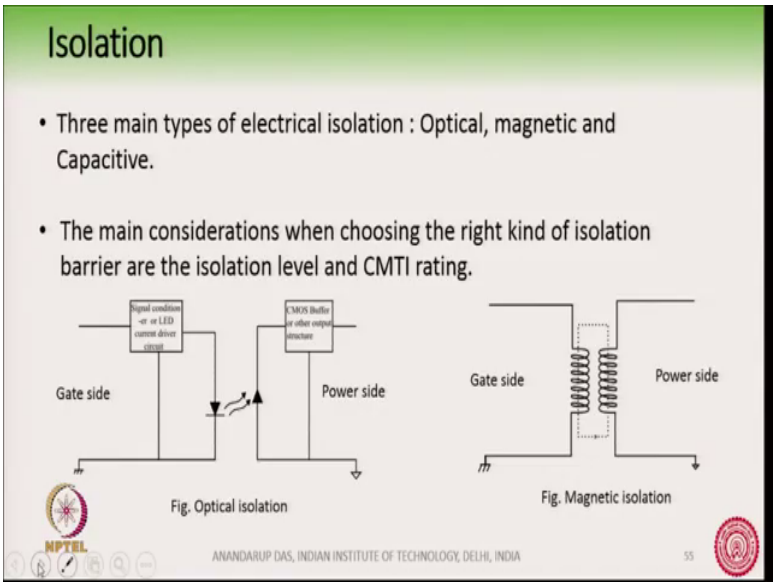

So, optical isolations, magnetic isolation or capacitive isolation are possible ok. So, gate driver ICs often give you a voltage rating that how much is the isolation how much isolation in terms of voltage, that is given in the gate driver IC. So, based on your application you can

choose a isolation voltage with a certain safety factor ok. But apart from this there is one more important rating, that you should also look into is the CMTI rating.

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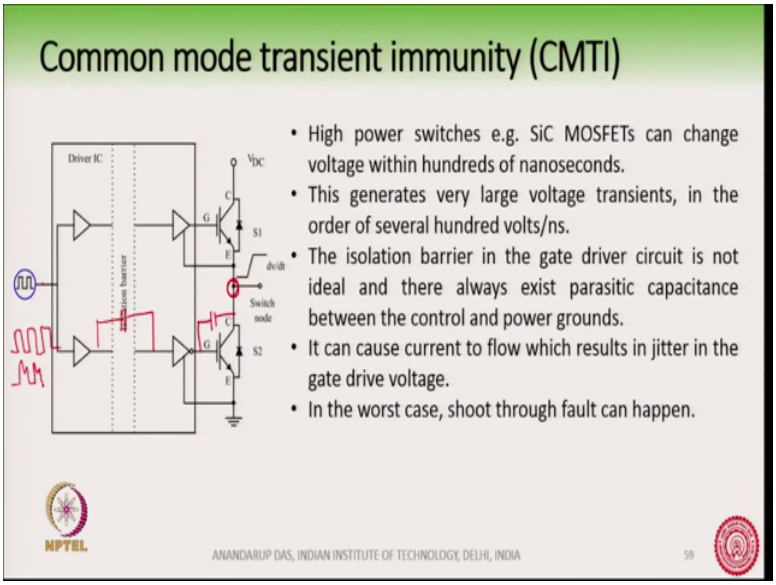

Now, What is CMTI? CMTI is a common mode transient immunity. And this is very important in particular for high switching frequency devices like, silicon carbide MOSFETs. Now they are very fast they can turn on and off very fast. So, what happens with silicon carbide MOSFETs or high switching frequency IGBTs also is that a large voltage transient can occur at between the collector emitter voltage. So, for example, here you can see when this device is turning off, the voltage V CE has a very large dv by dt across this terminal ok. Because it is turning off maybe within hundreds of nanoseconds ok. So, and this voltage V DC can be several hundred volts maybe 1 kilo volt also.

So, this voltage during turn on or off can change drastically ok in the order of several hundreds of volts per nanoseconds ok. Now although the isolation barrier in the gate drive circuit is present, but they are not ideal. So that means, there is a parasitic capacitance here. And also we know that the gate collector terminals have a capacitance between them. So, what happens is that, when there is a high dv dt at this point, when there is a high dv by dt the circuit takes a gets a path through this parasitic capacitors to flow towards the control side ok.

So, because of this there will be noise and jitter on the control side on the gate drive voltage. So, this voltage here instead of having like a perfect pulse you will see that there is a pulse, there is a there are the pulse shape is getting deteriorated. And it has jitter in the gate drive voltage. And in the worst case it may happen that there may be a shoot through fault. So, the Common mode transient immunity is something which is specified, as a quantitative measure for the gate driver circuit against such noise common mode noise ok.

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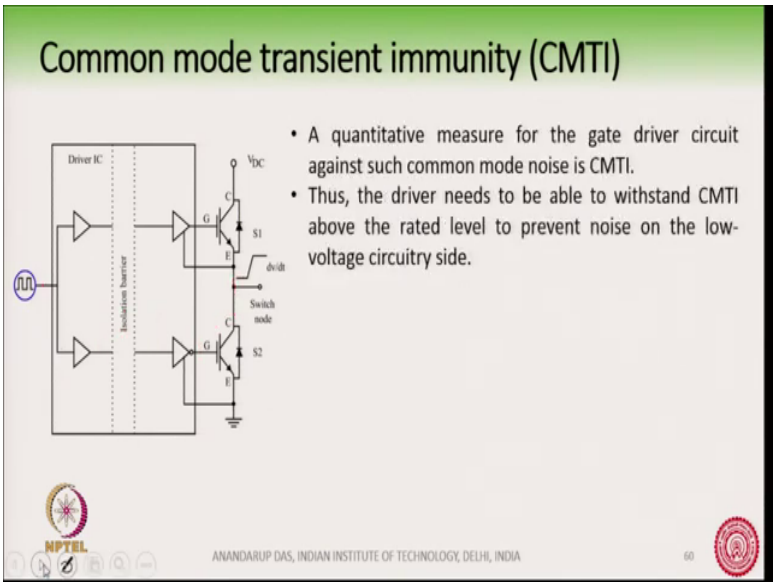

So, the driver needs to be able to withstand CMTI above the rated level, to prevent noise on the low-voltage circuit. And this is given as a value in the gate driver.

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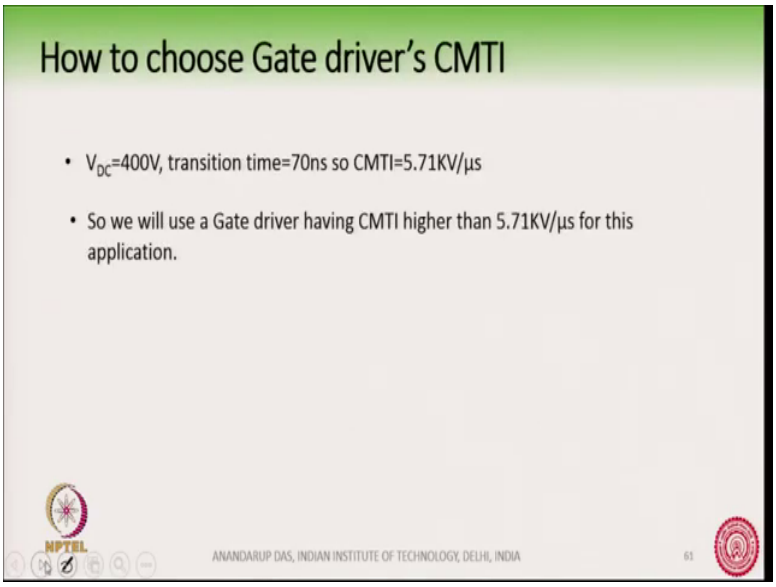

So, suppose let us take an example if V DC is 400 volt and the transition time is about 70 nanosecond so, CMTI is 400 volt divided by 70 nanoseconds. So, 5.71 KV per microsecond. So, we must use a gate driver board oh sorry gate driver IC having a CMTI value which is higher than this 5.71. And this is available in the datasheet of these gate drivers, and you should choose such a value ok. It is very important the CMTI value is very important for silicon carbide or if these high switching frequency applications, high switching frequency devices.

There is also something, which you will see sometimes being used is the UVLO Under Voltage Lockout.

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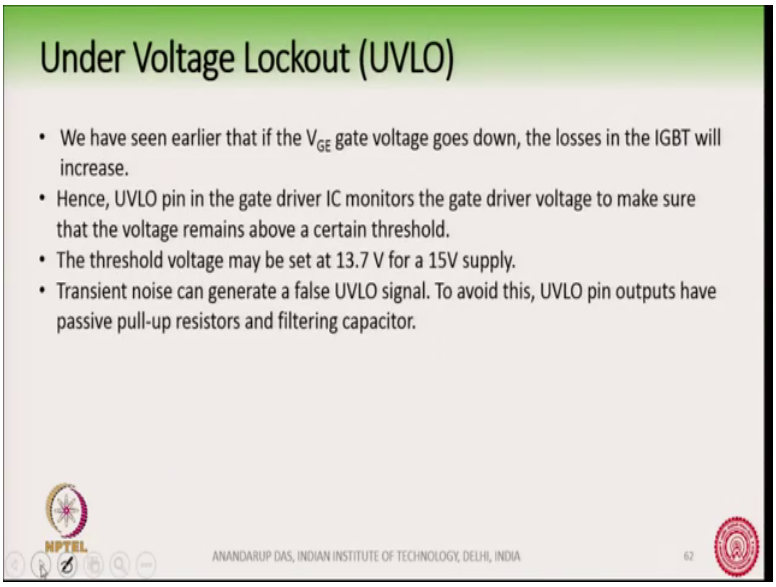

What is that? Under voltage lockout is also a protective feature in the gate driver ICs. So, what happens here is that if V GE voltage goes very low, then we know that there are associated problems. The losses will increase and also the conduction loss will increase.

So, the UVLO pin in the gate driver IC there is always an under voltage lockout pin in the gate driver IC, that monitors the gate driver gate emitter voltage ok. So, it makes sure that this voltage is below a is above a threshold value. The threshold voltage may be in the order of 13.7 volt for a 15 volt supply ok. So, but remember there may be a transient noise sometimes for a false UVLO signal.

So, you generally this UVLO pin outputs have passive pull up resistors and filtering capacitors ok, to get rid of the transient noise and a false UVLO signal.

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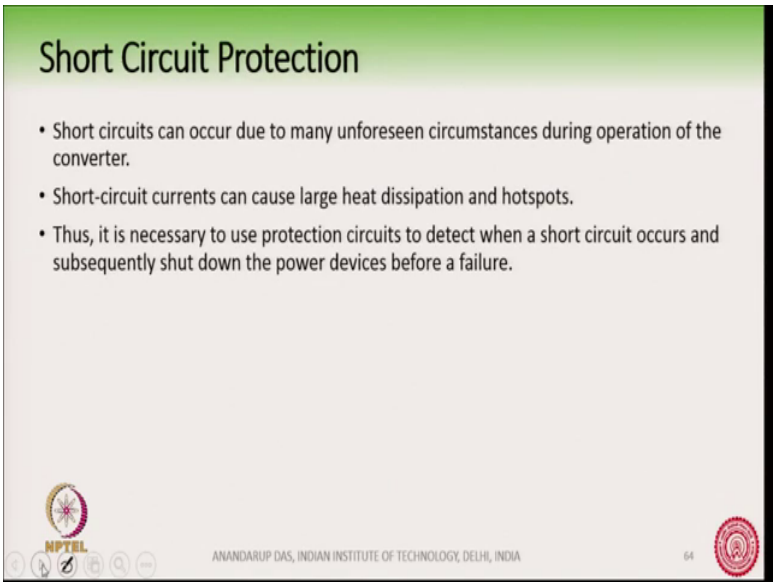

Another thing this is very important in gate drivers ICs is the how it protects the short circuit? Ok. Now often for many unforeseen circumstances we see that, short circuit will happen in the converter. So, during short circuit a large dissipation of heat will happen inside the device and hotspots will develop and eventually the device will burn. So, the gate driver has the important job of withdrawing the pulse and shutting down the power device in a safe fashion, before a catastrophic failure occurs.

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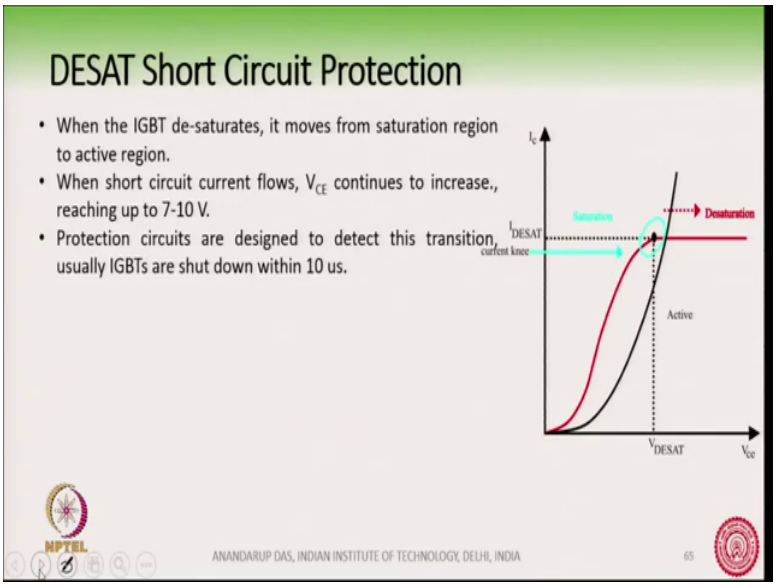

So, basically how does it do that? Basically, it monitors the collector emitter voltage. For example, in an IGBT if you think of the, IGBT protection the IGBT protection is called as a DESAT short circuit protection ok. What is DESAT? DESAT means de saturation. So, when a high current flows through the IGBT, you can see suppose this is the IC versus V CE characteristics of the IGBT here. And that characteristics typically looks like this maybe a little bit slope here slight upward slope here, but more or less the characteristics is look looks like this.

So, normally the IGBT for example, is operating normally in the saturation region. Because we would like to have the minimum voltage drop across it, when it is fully turned on. But now when a short circuit happens? Then a large current starts to flow and this a large current

starts to flow and this causes the IGBT to move into active region. In active region the V CE voltage is substantially high, and it is of the order of 7 to 10 volts ok.

So, protection circuits are designed inside the gate driver or with some components outside they will detect this transition, where they will see that ok, normally when the IGBT is turned on, the normal V CE voltage may be between 1.5 and 2.5 volt. But if there is a short circuit this V CE voltage suddenly shoots up to 7 to 10 volt. So, by seeing this change in V CE they will be able to this gate driver IC will be able to detect a short circuit condition, and therefore shut it down the IGBT. Usually IGBTs are shut down within 10 micro second maybe 7 8 microseconds only ok. Again, depends on how is the short circuit withstand capacity of the device.

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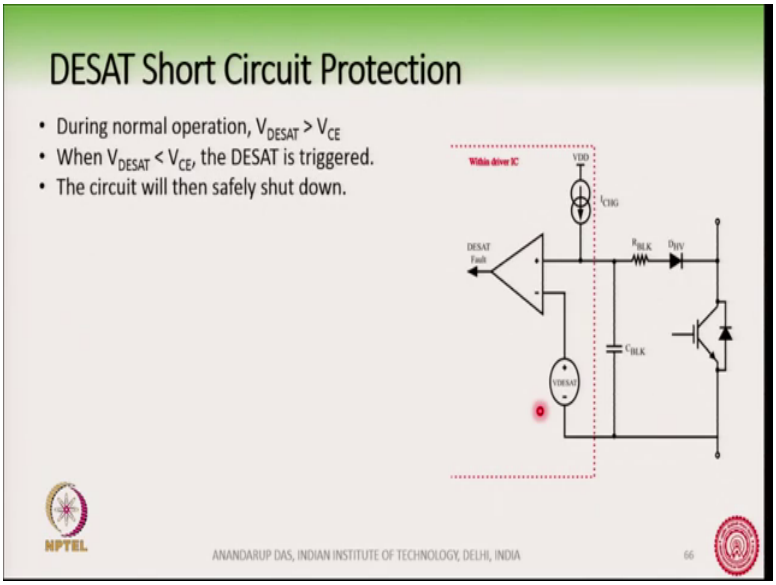

So, for this we have a circuit I will not go into the details of this circuit. But basic idea here is that, we have so this is the driver IC here. There is a additional voltage source inside the driver IC the driver IC has a voltage source inside which is made using analog circuits and then, it monitors this voltage here across the collector emitter of the IGBT. So, when this voltage collector emitter voltage crosses this V DESAT, then this op amp is forward biased and then this pin probably will go high ok.

So, that circuit will detect the short circuit condition in the IGBT ok. So, we will also need this diode because remember that this V CE voltage, when the IGBT is off? This is the total DC bus voltage and the diode has to block the DC bus voltage from coming across the op amp. In addition to that, there is also this capacitor C blanking and there is also resistance R blanking. Because you see here what means if you do not use these components what happens is that every time the switch is turning on this IGBT is turning on, it is going from the VDC voltage to suppose 2 volts, which is the VCE on of the device.

So, suppose if the DC voltage is 600, so from 600 it goes to two volt. And suppose this VDESAT this voltage is about 7 volts for example. So, every time the device will turn on it will move from 600 will cross through 7 and will move to 2, 2 volts. So, every time it crosses this close to 7 volts this will this op amp will be triggered, which we do not want. We want the DESAT protection to only work, when the device has been fully turned on and afterwards if there is a short circuit.

So, therefore, there must be a delay inserted in the circuit. Why the delay? Because we would like to wait for the IGBT to fully turn on ok. And then this DESAT protection should get active ok. Otherwise every time the IGBT is turning on the DESAT protection will be activated ok, as it moves from 600 volt to 2 volt for example. So, this delay should be ideally at least the delay for which the IGBT is turning on, that is the total time delay of stage 1 to 4, that much delay must be present if not more.

So, that delay is provided by this RC circuit here along with a charging current here ok. So, that part we will not go into the details of this circuit its not necessary. But this C blanking

will provide you the delay for which the once the IGBT has settled down to 2 volt. After that after that delay, the short circuit protection gets activated. So, that when the IGBT is fully conducting then a short circuit happens then the voltage will rise from 2 volt to 7 8 volts.

Then the DESAT protection gets triggered and it will shut down this IGBT in a safe fashion.

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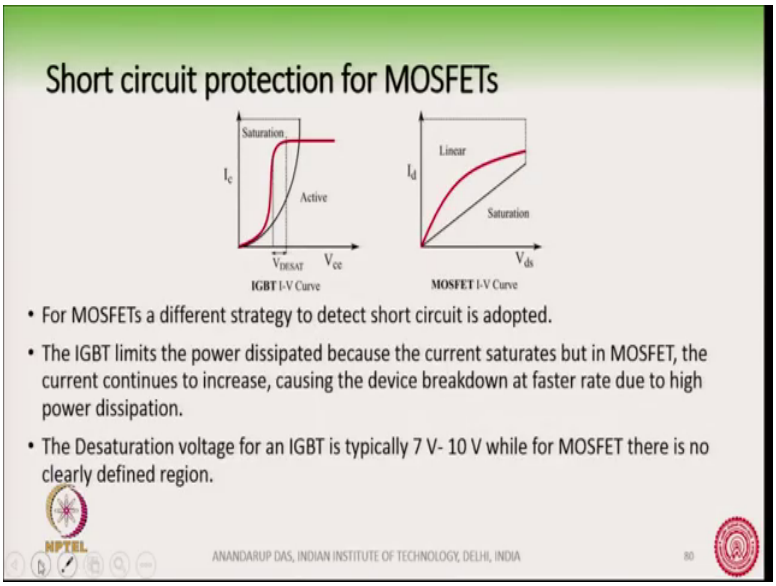

Apart from this, we should also understand that short circuit protection for MOSFETs is slightly different, than that of IGBT ok because of the characteristics ok. In case of a IGBT during short circuit you can see the characteristics looks like this, but in case of a MOSFET, the I d versus V ds characteristics is like this. And this means that when a short circuit happens, the current continues to increase in the MOSFET and causing this device to break down at a faster rate ok.

So, the desaturation voltage of IGBT although it is 7 to 10 volt, but in case of a MOSFET there is nothing called as a clearly defined region that ok, your monitor V ds and you will get the correct short circuit condition. So, for MOSFET this strategy does not work.

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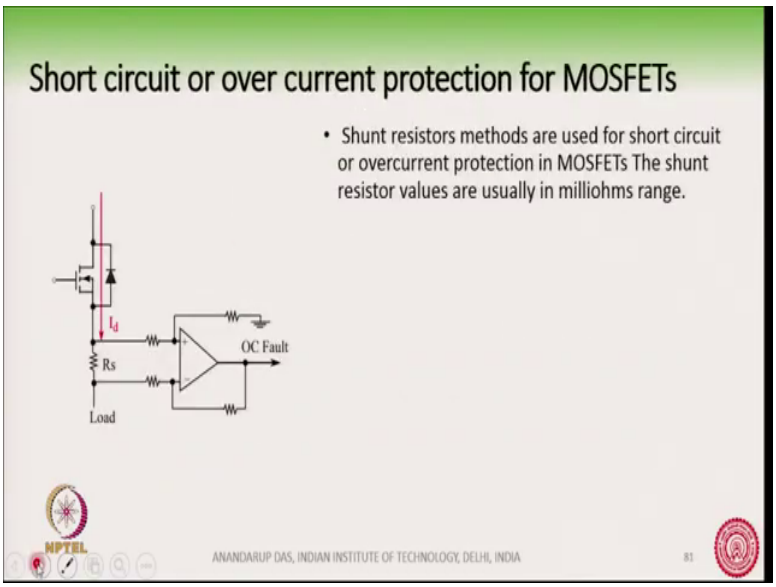

The strategy of monitoring the V ds voltage. Instead in case of MOSFET, we use shunt resistor methods ok. The shunt resistor values, the voltage across the shunt resistor is monitored. And then it will cause this op amp to trigger as the voltage goes a beyond a certain limit. So, this is how short circuit or overcurrent protection for MOSFETs work ok. So, with this we conclude the our discussion on the gate driver circuits.