Power Electronics
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Lecture 2 - Power Devices: Diodes and SCR

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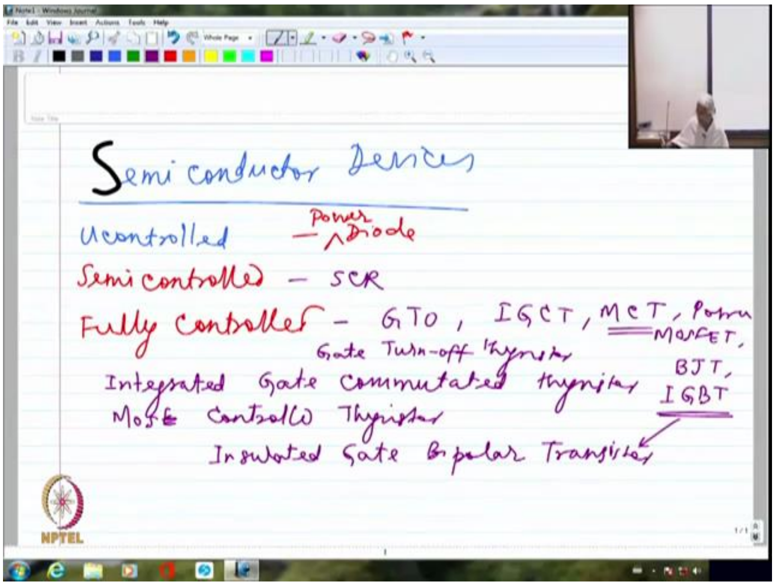

We are going to start on Devices. So we will have 3 different kind of devices that we will have to discuss in this particular course. So uncontrolled devices, then semi-controlled devices and fully controlled devices. These are the 3 types of devices that we are going to discuss. As far as uncontrolled device is concerned, as I told you the major device that we are going to discuss is diode.

And we always add a power as a prefix, so it will be a power diode that we will be discussing briefly because you guys know about diodes, there is hardly any difference between the two. So we will only highlight the differences and if at all in the operating condition if it is somewhat different I will also highlight that. And semi-controlled device, we are going to normally talk about SCR, silicon controlled rectifier.

Many of the books use thyristor and silicon controlled rectifier synonymously but thyristor actually indicates the family of devices. Some of them may be in fully controlled configuration, some of them may be in semi controlled configuration. So, I would rather say thyristor refers to normally a family of devices, some of them being semi-controlled and some of them being fully controlled.

So in fully controlled as far as the thyristor family is concerned, we have something called GTO gate turn off thyristor, then there is one more called IGCT that is integrated gate commutated thyristor. These 2 belong to thyristor family, yet it can be controlled during turn on as well as turn off. There is one more called MCT which has not become very popular, so it is almost you know extinct, MOS controlled thyristor. So metal oxide semiconductor controlled thyristor. So MOS controlled thyristor is MCT. So these are the 3 types of thyristor devices which are coming under the category of fully controlled devices.

SCR is particularly a semi-controlled device, only ON condition can be controlled OFF it is very difficult to control. You cannot turn it off very easily from the gate terminal, that is what I mean. Otherwise you have to take you know roundabout approach to turn it off, that is one of the problems with thyristor especially if I use it in a DC circuit because in a DC circuit, I will normally connect it in forward biased condition. How will I reverse bias it? Unless I apply a negative voltage, in AC automatically the voltage will become negative after some time but in DC it is not going to happen.

So generally, thyristor family of devices especially SCR it poses a big difficulty when I use it in DC circuit. Apart from that we also have power MOSFET, I am just adding power to everything. MOSFET is a normal transistor metal oxide semiconductor field effect transistor but power MOSFET is used in power electronics. Similarly, BJT, I should have added power. Power BJT, power transistor that is bipolar junction transistor.

And we also have another device which is exclusive to power electronics which is hardly ever used in electronics which is known as IGBT. IGBT is actually hybrid of transistor and MOSFET. Both of them hybridize together, a new device was developed by one of the Indian scientist who was sitting in, who is sitting still in NCSU North Carolina State University. So this was developed by him IGBT and it has become really popular.

And this is exclusively used for medium power ratings, hundreds of kilowatts rating, so this is known as insulated gate bipolar transistor. So, this is actually as the name indicates a gate will be insulated from rest of the device, so it is known as insulated gate bipolar transistor. So, these are the devices we will be discussing, in fact MCT I will not dwell much, IGCT very limited details are available.

It is an exclusive property of ABB, ABB is using IGCT extensively, so we do not have much of information about IGCT but rest of the devices at least I will cover the characteristics, their brief construction and how to select the particular device for an application, how to protect the device and what are other operating conditions we will be encountering, this is what we would be doing in this particular session.

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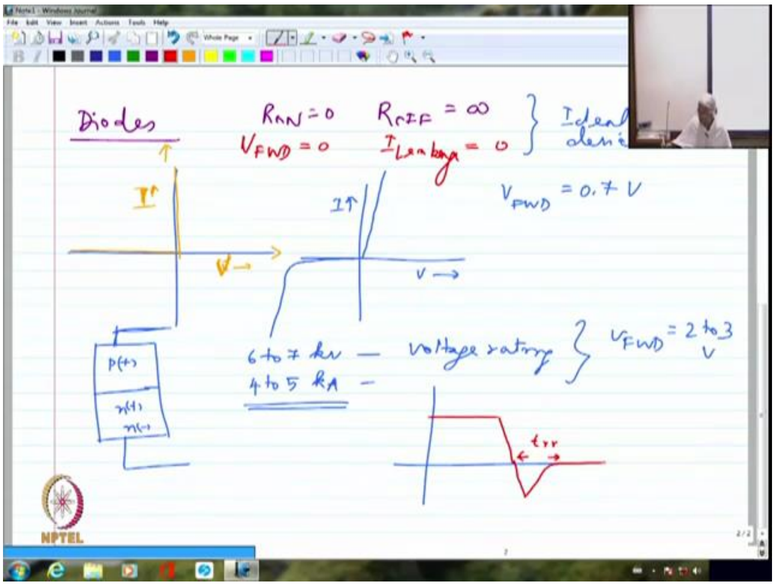

So let us start off with diodes. Normally in any ideal switch what we would expect is during ON condition it should have zero voltage drop and during OFF condition it should have zero leakage current. But definitely real devices are far from being ideal. That is why we call them as real devices. So apart from the aims or goals that I enlisted yesterday or in the last class, saying that we would like to increase the power capability to infinity, we would like the voltage capability to infinity, current capability to infinity, we would like to have the frequency to reach infinite value so that you will be able to operate it very fast and apart from that we should also look at on state resistance has to be minimized to zero.

If I want a device to be ideal, I must make the ON state resistance equal to zero. Similarly, R_{OFF} should be infinity which means I should have forward voltage drop to be zero and similarly $I_{leakage}$ during the reverse to be zero. So these are the characteristics that I would expect often ideal device. So also, is the case with, if I want the diode to be ideal I should definitely have these properties.

So if I try to draw the ideal characteristics of a diode, I should show it as though the current will increase you know vertically. I am talking about this as the voltage and this as the current So I am going to have voltage to be zero, so this is voltage and this is current. So, I am going to have essentially in the other condition the current is going to be zero, the reverse biased condition.

So this is the forward voltage, so this is the positive voltage, obviously voltage is increasing in this direction and current is increasing in this direction. So this should have been my ideal characteristics. So we would normally see that the current starts increasing after a little bit of forward voltage drop and it increases you know steeply, the current increases steeply like this.

And of course, on the other side the voltage, the current will be zero for a long time but if you increase the voltage beyond a particular value where the device would breakdown, I am going to have a steep increase in the current and that is the destructive breakdown. Most of the times it will be a destructive breakdown. So this is the reverse voltage, so this is the voltage and this is the current and I am going to have the real characteristics somewhat like this for the diode.

Normally for the electronic diodes what we use at low power level, we will see for a silicon diode V_{FWD} will be about 0.7 volts but in this particular case when we are using it for higher ratings, we might increase the length and construction wise what is done normally is there will be N- substrate with a very light doping and on that we will make P+ and N+.

So excess amount of doping is done on N- substrate. So normally what is going to happen is that you will see that the resistance is somewhat larger because of which, ON state resistance I am talking about, so the forward voltage drop will also increase. And if between anode and cathode, if am going to apply a large voltage because it is a large power rated device, in all probability the length of the device also has to increase somewhat.

So if you look at the normal diode that you use in electronics' lab to be really-really small but if we look at power diodes which are rated single-handedly, they can handle 25 to 30 megawatts, some of them can handle 25 to 30 megawatts single-handedly, so I may have 6 to 7 kilovolts as the voltage rating and 4 to 5 kilo amperes as the current rating. So if this is the rating of the device, the maximum current and maximum voltage that can be borne by the device then obviously it is going to handle anywhere between 24 to above 30 or 35 megawatts.

So which means it has to be definitely longer, so the voltage drop can go as high as 2 to 3 volts. When it is actually in on condition you can see that the voltage drop can go as high as 2 to 3 volts but 2 to 3 volts out of 6 kilovolts or 7 kilovolts is miniscule. Whereas when you work with 15 volts circuit, 0.7 volts itself is a big deal, so you definitely would not like to increase the voltage drop any further. Then it is far from being ideal.

So these diodes can handle, you know can have a voltage drop of almost 2 to 3 volts most of the times. Now as far as this diode is concerned because it can single-handedly handle such a large value of current, it also takes a little while before it turns off. So generally if you look at the turn off characteristics of a diode when you are reverse biasing, maybe the current was originally like this.

The current would come down rapidly, it will go very briefly into the reverse condition, very very briefly and then it will come down to 0 current or leakage current, this is the way normally the diodes depict the characteristics as far as the current is concerned. So this particular duration from where the current is becoming zero to the current is becoming negative and then coming back to zero this is known as t_{rr}, reverse recovery time.

So, the reverse recovery time essentially depends upon how quickly recombination takes place and all the charge carriers are swept out and then ultimately nothing is presented. The depletion layer is again built up. So that takes up a little more time especially in the case of a power diode because the number of charge carriers will be enormously high. Enormously high, because we are going to have a huge amount of current being carried, so all of them recombining will take at least a few microseconds sometimes. So reverse recovery time reduction is one of the key features as far as the research in diode is concerned. They want to improve that as much as possible so that you would be able to operate it in high frequency of operation. If it can be operated in high frequency that means it has to recover very fast, that is what it means. So reverse recovery time has to be brought down if I want to operate it in high-frequency circuits.

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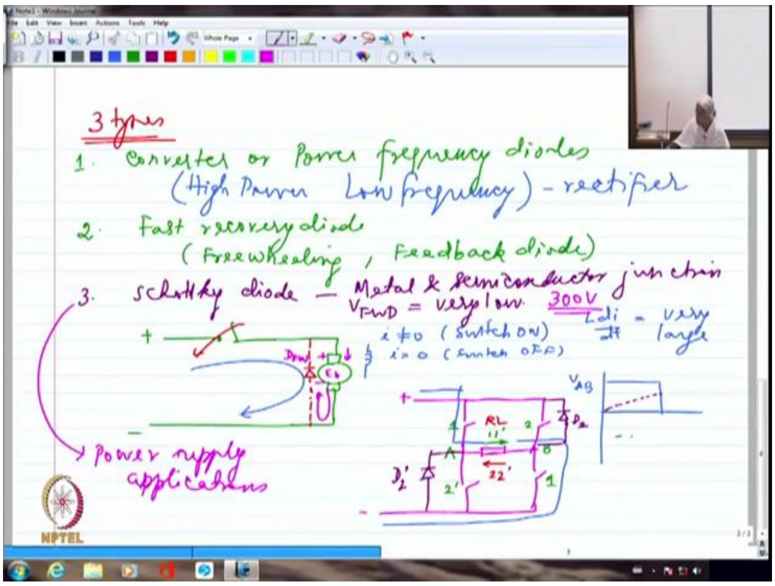

Now there are mainly 3 types of diodes we encounter in many of the power electronic circuits. One is converter or power frequency diodes. Power frequency is obviously 50 hertz, so we use it for rectification in most of the cases with the 50 hertz supply. So in those cases we call them as power frequency diode and that is 20 milliseconds cycle. So 10 milliseconds correspond to positive half cycle, another 10 milliseconds corresponds to negative half cycle, so I have sufficient time for the recovery. I do not have to worry about improving the reverse recovery.

So power frequency diodes are available at extremely large ratings like what I told you about 30 megawatt or 25 megawatt they are all power frequency diodes and they act pretty slowly compared to rest of the devices that we see in power electronics. So these are less costly, very robust, available at high power ratings; so we would be able to use them for high-power low-frequency applications.

So these are generally high-power and low-frequency applications. So they are pretty slow and they can handle very very high-power and the major application is normally rectifier that is the major application.

The second type of diode we normally see again in the market is fast recovery diode. Fast recovery diode as the name indicates it has to recover from the conducting condition to the non-conducting condition very quickly, as quickly as it can. And these are used generally in two types of applications, one is freewheeling, and other one is feedback diode.

Let me explain what a feedback diode is and what is a freewheeling diode because we will revisit this when we go to chopper and when we go to the inverter. Let us say I am using a chopper circuit, I have a DC supply here, for controlling the speed of a DC motor.

So I have a motor here and I am going to apply the voltage you know intermittently with the switch. The switch is not a mechanical switch, it is a semiconductor switch, I am not going into the details of the semiconductor switch, it is ON OFF control switch obviously, so I should be able to turn it OFF also. It cannot be a diode that is what I mean. So I am going to have whenever the switch is ON, so if we are turning the switch ON, at that time I am going to have a current flowing like this.

This is going to be the current but as you all know motors have some inductance, so if I try to open the device then I am going to have a huge amount of $L\frac{di}{dt}$ because the current will be forced to go to zero instantaneously which is definitely not good for the switch as well because if I am having an inductance here that means I am going to have, initially I is not equal to zero when the switch is on.

When I am going to turn the switch off I will be equal to 0. And if the switch is off and I becomes 0, abruptly the current goes from a finite value to 0 in no time. So I am going to have a huge amount of $L\frac{di}{dt}$. So, $L\frac{di}{dt}$ will be very large if I try to simply open the switch without having any alternate path for the current. So to give an alternate path for the current I would like to put the diode here.

This is the diode that I am going to put right across the motor drive, and I call that as a freewheeling diode. Freewheeling diode is that diode which will carry the current which is stored, which is because of the energy stored across the inductance. So, it is like a flywheel, it is essentially trying to you know de-energize the inductance by circulating the current through itself and whatever is the load.

So now during freewheeling condition if I try to look at the current, the current will go like this through the diode. The current is still flowing in the same direction, please note that. The current direction cannot change in an inductance, it has to remain in the same direction and now the switch is open, when the switch is open the freewheeling diode let me call this as D_{FW}.

Freewheeling is FW, so I am just writing D_{FW}, so the freewheeling diode carries the current when I am switching off this semiconductor switch and now the conduction path is essentially through the diode, so it is as good as short-circuiting the motor drive. I have short-circuited the motor drive with the help of a diode but the energy stored in the inductance is finite.

So obviously the current cannot go to infinity, current has to slowly decrease because inductance stored energy previously $\frac{di}{dt}$ would have been positive, now $\frac{di}{dt}$ would have been negative because there is no other source that is available for the motor drive. The back emf will also be opposing, I hope you understand. If I try to look at the back emf, the back emf will be plus here and minus here that is how Eb will be which is opposing the current obviously.

So I will have the diode taking over the current and I call this as freewheeling diode and this is going to happen repeatedly every time I turn on and turn off the switch, which means this diode has to work as fast as the rate at which the switch is working. So obviously it cannot be doing it slowly, so that is why this is known as a fast recovery diode. It has to recover fast and it has to go along with the switch. Whenever the switch is not conducting, this will conduct and vice versa, that is how it will be.

There is one more application which I told you as feedback diode. For this we should know roughly what is an inverter. So let us say I have a single phase, DC to single phase conversion circuit. So these are the 4 switches, this is plus and this is minus. And I am going to have a load connected here. Here is where my load is. The load is here, so let me call this point as A and this point as B.

Let me call this as 1, this is 1', this is 2 and this is 2'. Whenever I am having 1 and 1' conducting, the current would go in the load in this particular direction. This is for 1 and 1' . Whereas if I have 2 and 2' conducting I am going to have the current going in the opposite direction, you get my point? So I would have alternating current flowing through the load depending upon you know whether I am keeping 1 and 1' ON for some time and 2 and 2' for some time and how frequently I am doing the switching action that will decide the frequency of this alternating current that is flowing through the load.

So I can adjust the frequency very-very well by adjusting the rate at which I am operating these devices 1, 1' and 2, 2' and so this becomes an inverter from DC I am converting this into AC. Please note again that these switches have to be turned OFF forcefully because it is connected to DC, so if I actually have a thyristor for example SCR it is going to continue to conduct.

Because I told you that as far as thyristor is concerned, turn on is in our hands but turn off is not in our hands. So normally we use probably IGBT or IGCT or MOSFET or BJT, one of them for this device. Now let us say this load is RL load, R and L in series. Now if I am having 1 and 1' ON I am going to have a current going like this, go through like this through this green and then it is going to come through like this.

This is going to be the current path when 1 and 1' are ON. Now I want to start the negative half cycle, So if I try to draw the voltage I am probably going to have VAB when 1 and 1' are ON I am going to have positive voltage. And if I try to draw the current maybe the current would have been increasing like this. RL transient. So obviously the current will increase. It would not have reached steady-state yet in all probability.

Now I want to turn on 2 and 2', before that I would like to turn off 1 and 1'. When I turn off 1 and 1' the current is still not 0 and I have an inductance sitting in the load. So obviously I cannot make inductive current abruptly 0, if I do that I will get a very large voltage, so I should provide an alternate path. So for providing an alternate path the current is still flowing in this direction, I can put one diode here and one more diode here.

The current is flowing in this direction, so if I may call this as D_2 and D_2' I will have the current flowing through D_2 and D_2' back to the supply. So the supply is actually getting the current like this. So it is flowing into positive terminal and flowing out of negative terminal through D_2'. That means the stored energy in the inductance is charging the battery, if I say it is a battery the battery will get charged from the stored energy in the inductance, that is what is going to happen.

So it is feeding back the energy that is actually already there in the inductance, so this is generally known as the feedback diode. So feedback diodes are an essential feature of an inverter whenever I have RL load.

If I do not have RL load, if it is only resistive load which is a very-very rare thing in actual electrical circuits I am not going to be using a feedback diode but if there is inductance, I definitely need to use a feedback diode. If I do not use a feedback diode, my devices will conk out right away because $L\frac{di}{dt}$ will result in a very very high voltage. So, the devices will conk out because they are designed only for a particular value of voltage.

So fast recovery diodes are used in choppers generally as freewheeling diode, even in rectifier it may be used as a freewheeling diode but in all probability, it need not be fast recovery if it is a 50 hertz rectifier but in inverters and in choppers normally we operate them in kilohertz or tens of kilohertz, so they have to be fast recovery diodes. The third type of diode is Schottky diode.

Schottky diode is basically rather than doping the semiconductor with P and N, it may be a simple semiconductor material of N which is having a junction with metal. So you will have a metal and semiconductor junction, one of them acting like an anode the other one acting like a cathode and that will function like a diode. So in Schottky diode because there is a metal and semiconductor junction I am going to have the resistance of this material will be generally much smaller compared to a normal semiconductor diode. So the forward voltage drop will be as low as 0.1 or 0.2 volts, so V_{FWD} will be very low but on the other hand the leakage current can be higher somewhat. The leakage current could be somewhat higher because the resistance as such has come down somewhat.

So, because of which forward voltage drop coming down but simultaneously I am going to have the leakage current slightly increasing. These generally are designed only for lower wattage rating. Generally, these are not available beyond 300 volts or so and maybe a few tens of amperes, 10 or 20 amperes, that is it. Nothing more than that, so the rating that is available in Schottky diode generally is very small because of the limitations that we have in the form of leakage current.

Leakage current will otherwise increase tremendously if I go for higher and higher voltages. So generally they are designed only for lower power ratings, these are mainly used in power supply applications. Again power supply applications because if you look at many of the regulated power supplies that we have in the lab which are definitely not SMPS, they are not SMPS normally, they are regular linear regulated power supplies, those will be 15 volts or 5 volts or 3.3 volts and so on.

Out of that instead of dropping 0.5 volts if you drop only 0.2 or 0.1 volts it is better, you have a better regulating capability. So you would like to reduce the drop as much as possible in power supply applications. So because of which normally Schottky diodes are used in power supply applications.

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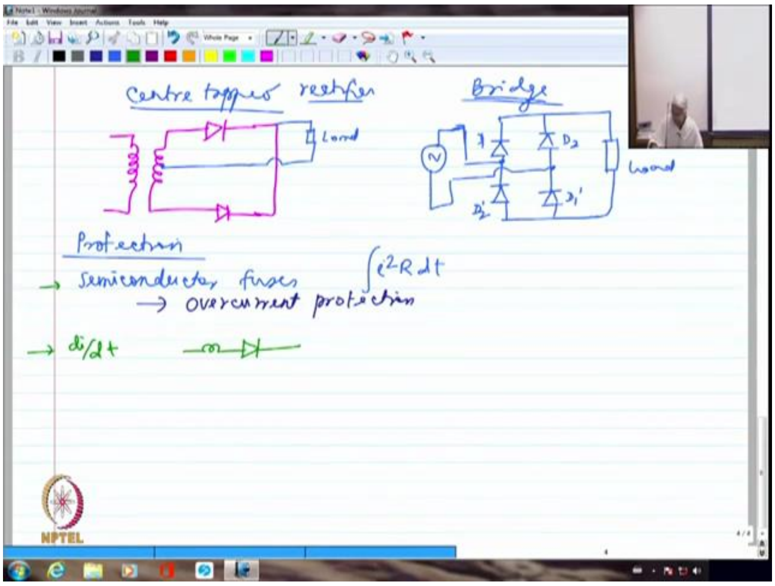

And similarly in power supply applications again if you look at the rectifier that we use in power supply normally, you would see that if this is my output side of the rectifier invariably I will use one Schottky diode here, one more Schottky diode here, I would connect them together and from the center tap I would connect it to the load. This kind of rectifier we call as center tap rectifier, I do know whether you have come across this.

So this is the center tap rectifier. Center tap rectifier will have generally a transformer always associated with the rectifier circuit and you will have only one diode conducting at a time. At a time you will not have more than one diode conducting, so which means this is going to have only 0.1 or 0.2 volts drop if I am talking about a Schottky diode. Whereas you guys must have learnt about bridge rectifiers as well.

So if I look at a bridge rectifier, bridge rectifier is somewhat like this, right? And here is the load and I am going to have the power supply connected here, this is the power supply connected. I do not need a transformer that is a major advantage, no doubt but I will always have say D_1 and D_1' conducting or D_2 and D_2' conducting. 2 diodes will conduct at a time.

Without 2 diodes it will not work. So I will have the voltage drop corresponding to 2 diodes in this case whereas in a center tap rectifier I will have the voltage drop only corresponding to 1 diode. So generally center tap rectifiers are preferred in power supply applications because I have to only manage 1 diode drop. Whereas in the other case 2 diode drops which will amount to maybe especially if it is a silicon diode 1.5 volts, 1.4 volts, I may get a very large drop out of 5 volts power supply which is definitely not a good thing.

That is the reason why generally bridge rectifiers are more used with motor drives or large power applications. Whereas center tap rectifiers are generally used with power supply applications. And power supply applications want to minimize the drop, so Schottky diode also go hand-in-hand with this. So much so for the 3 types of diodes. Now as far as the diode protection is concerned, how do I protect the diode? Again whatever voltage is over current, high $\frac{di}{dt}$, high $\frac{dv}{dt}$. Normally we use semiconductor fuses in series with the diode. Semiconductor fuse should have an i^2t rating. i^2R is the power loss which is also manifested in the form of heat. So, $\int i^2R\,dt$, this is what gives me the overall heat generated. So i^2t rating corresponds to how much is the heat a particular device can withstand. In the form of energy, we talk about this in the form of energy. So i^2t rating of a fuse has to be smaller than the i^2t rating of the device, so that the fuse conks out first before the device is affected.

That is the reason why we have to use a fuse rating whose highest i^2t rating is smaller as compared to the device rating itself. So device will not conk out, before that the fuse will burst that is what will happen. So semiconductor fuses are normally used for over current protection.

So if a large current flows, more than the rated current of the device in all probability the fuse will first go off because of which the device will be protected. Now other hi-fi protection is normally used for the diodes and as far as the overvoltage is concerned sometimes we may use this zener but most of the times forward conditions it will not have much voltage, so do not have to worry about it.

In the reverse condition we might have to use the zener, sometimes we might use a zener that is what we will do. But generally overvoltage protection of diodes is not talked about much because hardly ever we subject it to a higher rating than what it is required to withstand normally. But $\frac{di}{dt}$ protection we have to give normally for the diode and $\frac{di}{dt}$ protection is normally given by having a small inductance in series with the diode. If I have a small inductance, it will automatically reduce the rate at which the current is rising. For example, we actually looked at the chopper.

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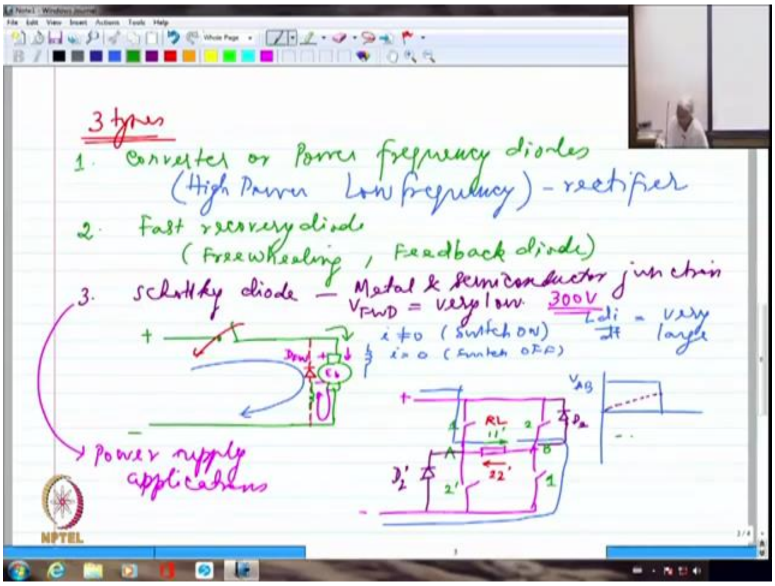

Here if you look at it, maybe the DC motor drive was carrying hundreds of amperes of current, when the diode is taking over it has to abruptly take that 100 ampere which is definitely not good because $\frac{di}{dt}$ in that case will be enormously high. So the semiconductor material can breakdown. So if I put a small inductance here in series with the diode, very small inductance.

Very often what happens is, if I have a thick conductor connecting the diode to the DC motor drive that itself will have an inherent inductance which is good enough most of the times, but we will have to make a calculation before we decide whether that inductance is good enough or whether I have to add some external inductance so that the current $\frac{di}{dt}$ is limited within whatever is the tolerable limits of the device. So $\frac{di}{dt}$ protection as the rule is always implemented for all devices by having an inductance.

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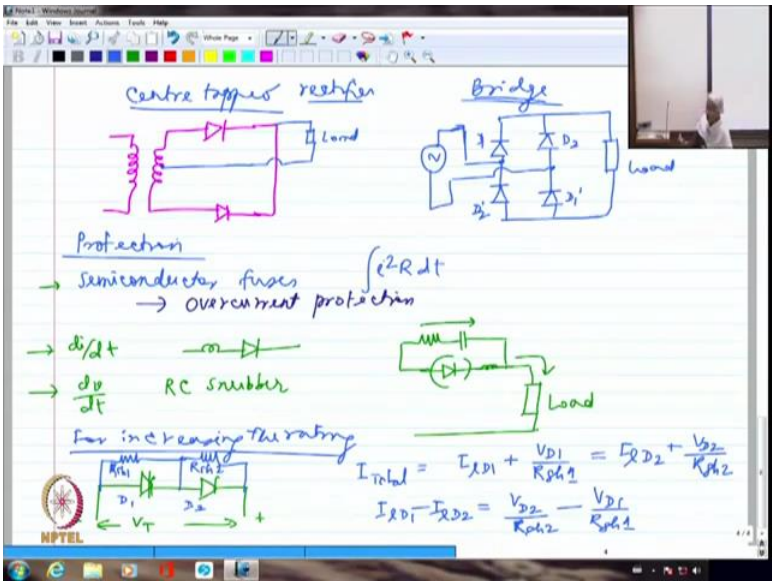

Whereas $\frac{dv}{dt}$ protection this is done with the help of something called an RC Snubber. We use something called an RC snubber for making sure that the $\frac{dv}{dt}$ protection is implemented. So let us say I have a diode and I have a load. And I am going to have probably you know the lead inductance, it is not going to be very-very small, maybe it is some value which can still affect the diode because probably the current is very high.

L can be small but $\frac{di}{dt}$ could be very large because of which I may have a large voltage coming across the diode if I do not give adequate protection. So let us say for some reason this diode will stop conducting and something else takes over. Or the current is trying to come down to very minimal value whatever through the diode, I am talking about the diode.

So maybe there is some other alternate path. If I am going to make the current through the diode abruptly 0, then whatever is the lead inductance L $\frac{di}{dt}$ will be a very large value of voltage, it will be coming across my device. So the device can breakdown. So if rather I give R and C right across this device. In which case at least there will be an alternate path provided for the current for a pretty short while.

So I will have basically, if the current had been flowing earlier like this, now it will try to probably flow through this and to the load. So now the capacitance will slowly get charged because the load current is now deciding at what rate the capacitance is charging. So the RC time constant will decide the rate at which I am going to have the increase in the voltage of the capacitor.

So, the voltage across the diode will also be somewhat limited by the RC time constant of the circuit. So, this RC circuit is generally known as snubber which will allow a gradual rate of rise of voltage across the device which will definitely not allow the device to breakdown because of high $\frac{dv}{dt}$. So, the snubber is commonly used in many of the semiconductor circuits to protect them against high $\frac{dv}{dt}$.

Similarly, inductance is used in many of the semiconductor devices to reduce $\frac{di}{dt}$ value. So, these are common features in many of the semiconductor circuits. Before we conclude the topic of diodes, very often I might have to use multiple diodes in parallel or multiple diodes in series if I want to have a higher and higher voltage circuit. For example, I told you that one particular diode can withstand 6 kV.

Let us say I have a 30 kV circuit which I want to operate with the help of a diode, then I might have to put at least 5 of them in series. In fact 5 would not be sufficient because I also have to include a factor of safety. In case there is a spike or in case it is an AC, RMS value may be 6 but the peak value will be 6 time $\sqrt{2}$, so I have to definitely put a factor of safety and then choose maybe 7 or 8 or 9 devices.

So if I want to increase the rating, I have to include many devices in parallel or series, so I may have maybe 1 diode and another diode for example in series to withstand a total voltage of V_T, V total. If it is conducting, I do not have to worry much because while conducting it is going to have a drop of a few volts, so there will not be very large voltage coming across the devices.

But when it is not conducting, if I am going to have plus here and minus here then it is not conducting I am going to have the entire voltage borne by these 2 devices together. Let us say each of these devices are rated for 6 kilovolts and total I have is 10 kilovolts, ideally I would like to have them 5 kilovolts each. If each of them block 5 kilo volts, that is the ideal condition, then I do not have to worry about their breakdown.

But by chance there is some inherent difference in their characteristics, maybe the leakage currents are different, then I cannot assure that both of them are going to have the same amount of voltage drop. Let us say one of them becomes 6.5 the other one becomes 3.5, the 6.5 fellow will breakdown. Because it is supposed to withstand only 6 kilovolts, so if I just put 6.5 kilovolts across it, it will breakdown.

So I have to make some arrangement, then I have a string of devices to make sure that the voltage division is equitable across all the devices. Only then I can operate them safely in series condition or parallel condition. For making the voltage distribution equitable, normally I will have one resistance and another resistance like this. These resistances normally will be of very large value.

They will be of large value, so let us say I call this as D_1, I call this as D_2 and I call this as R_{sh1} and this is R_{sh2}. So I am going to have actually the overall current

$$I_{total} = I_{lD1} + \frac{V_{D1}}{R_{sh1}} = I_{lD2} + \frac{V_{D2}}{R_{sh2}}$$

Now I should be able to write this as I_{lD1} - I_{lD2} which is the difference in the leakage currents of the 2 diodes. Inherently probably they are different because even in the same batch of manufacturing you cannot expect all the devices to exactly have the same characteristics. It may be of the order of microamperes but still there is a difference. So this is going to be the difference in the leakage current, $I_{lD1} - I_{lD2} = \frac{V_{D2}}{R_{sh2}} - \frac{V_{D1}}{R_{sh1}}$.

If I say that I have got 10 kilovolts and each of these are rated for 6 then the maximum I can have is the discrepancy is, one can have 6 kilovolts, the other one can have 4 kilovolts that is the discrepancy I can have so that the diodes will not breakdown. So I have the values of what can be V_{D2} and V_{D1} or difference between V_{D2} and V_{D1} which comes out to be 2 kilovolts in this particular case.

And I have the discrepancy in the leakage currents already given to me because the data sheet will give the maximum discrepancy that can exist in the leakage current is between these milliamperes to these milliamperes, that is what it will say. So I have this data with me from the data sheet of the semiconductor device and I have this V_{D1} and V_{D2} computed depending upon my circuit condition from which I should be able to arrive at the resistance times.

What can be R_{sh1} and R_{sh2} or I can assume one of them to be say 10 kilovolts I can get the other resistance to be whatever value it is. So whenever I have 2 diodes or 2 semiconductor devices connected in series and I want them to share a voltage, then I definitely need to connect some larger resistances in parallel so that I am able to you know arrive at, at least tolerable voltage difference among the 2 diodes.

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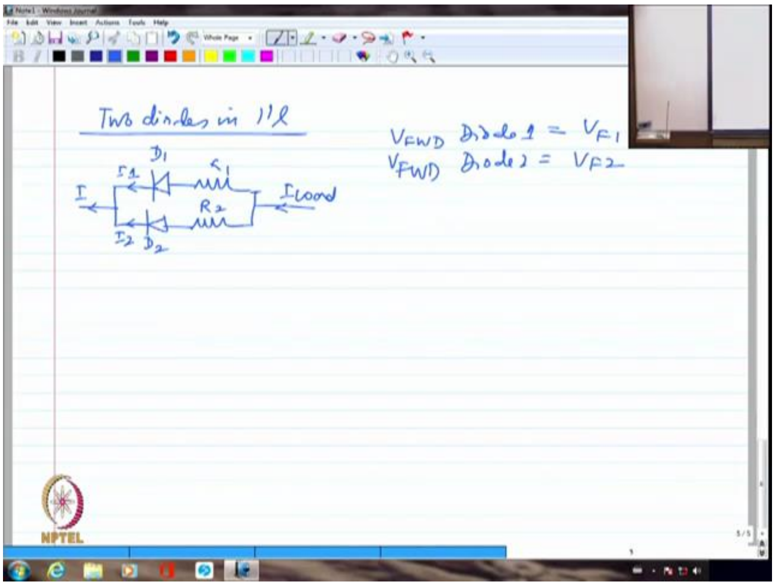

Similarly, when I am connecting 2 diodes in parallel when I connect 2 diodes in parallel, I will have 1 diode here and 1 more diode here. I will normally connect a small resistance, the series resistances will be really small in terms of milliohms or something. And I am going to have them carrying the current together, so this will be the load current.

So let me call this as D_1, this as D_2, let me call the diode current as I_1, this as I_2. So $I_1 + I_2$ will be I and this will be R_1 and this will be R_2, please derive this on your own I am sure you will be able to derive, how should you arrive at R_1 and R_2 so that the current discrepancy is within a particular limit? If I am saying that 10 kiloamperes is carried as a whole, each of them has to carry only 5 kiloampere but maybe they are rated for 6 kiloampere, so one can be 6 the other one can be 4.

You can calculate if the discrepancy is to kilo amperes. how much should be and forward voltage drops are different of course. So I have to say forward voltage drop of diode 1 is V_{F1} and forward voltage drop of diode 2 is V_{F2}. So you will equate the 2 voltages, that is all. And then you would be able to calculate how to arrive at R_1 and R_2 so that you are not having huge discrepancy in the currents. So much so for power semiconductor diodes.

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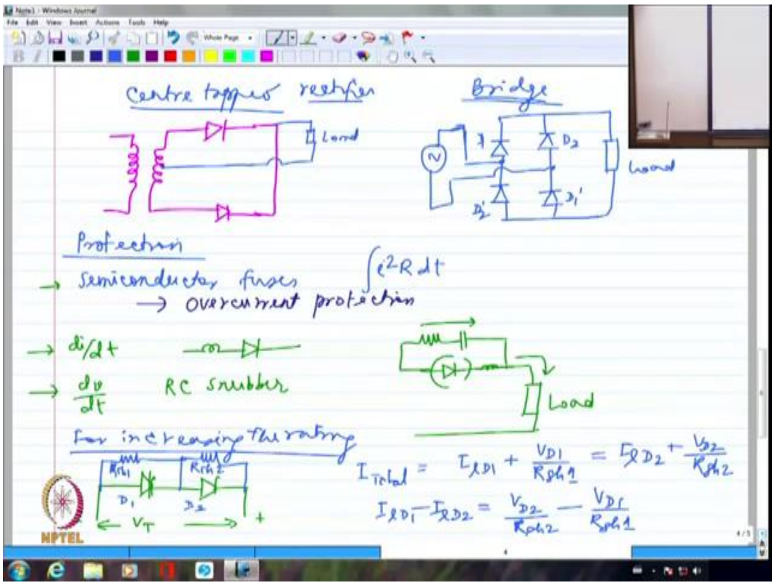

So in fact you can start looking at R_{sh1} equal to R_{sh2} that is not a problem. So you can take the same values for both so that you are protected against any eventuality, whether 1 leakage current that is a good question, I hope you got his question. He was telling that if I start assuming that the leakage current of this is higher than the leakage current of this and I do all the calculations and I get some R_{sh1} and R_{sh2}, if actual in actual you know a real life it is the other way around.

Then how do I make sure that the voltage is divided between the 2 diodes are still within the limits? So if you assume $R_{sh\,1} = R_{sh2}$ then you can just do the calculation for the safety measure as to what is V_{D2} - V_{D1}, so you can use the same resistance across both the diodes, it will work. One more thing is most of the times we tend to test at least a few diodes from a batch before we start using them generally.

And we will also make sure normally that the diodes are characterized as much as possible. Especially when you're using them in high-power applications we would not like to take a chance. Whenever we talk about high-power drives, especially motor drives almost 50 to 60 percent of the processor time goes towards protection. Rest of 30-40 percent only really goes towards control of the devices.

50 to 60 percent is going towards protection means we are really worried about the life of each of these devices because each of the device can cost crores of rupees, that is the reason we will have to be extremely careful about the devices. So we would definitely characterize each of

them normally, especially when we talk about very high-power applications. When we use it in milliampere or even ampere applications we do not care much.

That is why power supply applications we do not care so much about the life expectancy. Whereas high-power applications we worry too much about life expectancy of those devices and converters.

"Professor-Student conversation starts"

Student: How does the RC snubber protect the diode against high $\frac{dv}{dt}$?

Professor: Here, see because the current is stopping, we are expecting that there will be a very high $L\frac{di}{dt}$ but we are limiting basically the $\frac{dv}{dt}$ by having an RC value. So we are having probably from lower current flowing from here, from power supply is here from through this it is flowing like this.

Eventually the capacitor will get charged and no more current will flow. Maybe there is some other path for the load current; I am only showing the part of the circuit. So this is taking the brunt of the diode turning off and it is trying to take the entire current because of which the capacitance is getting charged and the rate of charging of the capacitor in this case is constant because the current is constant.

So you are going to have a linear rise in the voltage which will also make this voltage across the diode not go up drastically. So you are essentially avoiding any chance of the diode breaking down because of the sudden increase in the voltage, that is what happens. Maybe I should have shown this here, I think that is where the problem lies. This should have been shown here, then I think things are better because the inductance current now also is not abruptly removed.

I should have shown this here. What you ask is right because inductance is in series with the diode, nothing is avoiding it from getting the brunt of $\frac{Ldi}{dt}$. So, this connection should have come here before like between the inductance and the diode, it cannot come after the inductance, it does not make sense.

"Professor-student conversation ends"

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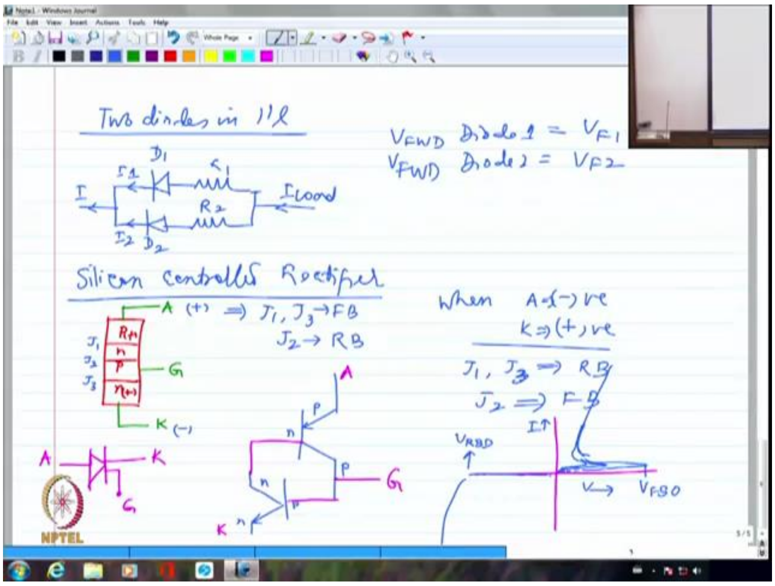

So as far as silicon controlled rectifier or SCR is concerned this is basically your 4 layered device. We normally say about diode as a 2 layer P and N. Transistor is a 3 layered device PNP and NPN whereas this is a 4 layer device, so I am going to have PN PN this is how it is going to be. And these 2 portions are heavily doped normally, this will also be plus, this will also be plus which means heavily doped.

These 2 are heavily doped normally. So they are like the emitters of any transistor. Transistor emitter will be normally heavily doped, so this is how it is going to be. And I am going to have this as the anode and this as the cathode and this will be the gate. So this is a 3 terminal device with an anode, cathode and the gate. And this is junction 1, J_1, this is J_2 and this is J_3. When we apply plus here and minus here and no power supply to the gate, I am going to have J_1 and J_3 forward biased. Because J_3 is towards N and it is going to get a negative voltage, so J_3 will be forward biased, J_1 will also be forward biased because P is connected to positive whereas J_2 will be reverse biased because this N is closer to positive, this P is closer to negative.

So I am going to have for this kind of power supply J_1, J_3 will be forward biased whereas J_2 will be reverse biased. So the blocking capability of this device heavily depends upon J_2 especially when I am in forward biased condition. So forward blocking capability of the device heavily depends upon J_2. If J_2 is really not strong enough it will not have the forward blocking capability properly for this device.

Whereas when anode is having negative and cathode is having positive power supply, then that I am going to have it the other way round, J_1 and J_3 will be reverse biased and J_2 will be forward biased. So reverse blocking capability heavily depends upon J_1 and J_3 in this case. Now if I look at this device, this is like a PNP transistor connected to an NPN transistor.

Only thing is that this base is going to be common with the collector of the second transistor. Similarly, this base is going to be common with the collector of the other transistor. So it is like two transistors connected back-to-back. So I am going to have basically let us say this is a PNP transistor like this. So I am writing this is P, this is N and this is P and I am going to draw one more transistor where this is going to be the emitter and this is the collector.

So this is again N and this is P and this is N. So this happens to be my cathode and this happens to be my anode. Now this N is connected here, similarly this P is connected here. So this is essentially the thyristor configuration or SCR configuration. Now this is my gate terminal. So if I do not give any power supply to the gate, if I do not forward bias it I am not going to have this transistor conducting at all.

But the moment I actually inject a current into this, gate current into this or if I forward bias this then this transistor is going to conduct. So I am going to have the base flooded with huge amount of charge carriers. The emitter is heavily doped, so I will see a huge number of electrons coming in and then that is going to go through the collector and that is going to fled the base of the next transistor.

So I am going to have essentially a small base current here in this transistor which is coming in the form of gate current will actually make a huge current flow through the collector and that is going to flood the base of the other transistor with a large number of charge carriers, so I'm going to have that again passing through the collector in the form of a large current. So it is like a you know huge amount of runaway condition.

A very large current is going to be generated with a very small gate current being injected in this side and once you start the conduction you do not have to do anything further. Even if you remove the gate drive because of the amplification you know repeatedly happening within the 2 transistors, the device is going to continuously conduct whether I like it or not. Initially you just need to give a small you know trigger.

The moment you give a trigger this will start conducting, a large collector current will flow which will flow into the base of this transistor. So again, a large collector current would flow, so this will become a loop here basically. So, we will see that the thyristor conducts with a very

very small trigger. SCR just will be able to conduct with a small trigger in the form of a gate pulse.

The moment it starts conducting it will be very difficult to quench the device because it is essentially increasing the current further and further. The current overall passing through the anode to cathode is limited only by the power supply that I am connecting and if at all I connect a load here that is going to limit the current, otherwise there is nothing else that is limiting the current within the device basically.

So that is the reason why SCR can be controlled only for the turn on and cannot be controlled for the turn off. For turn off it is very difficult to you know really bring the device into off condition, it is not going to be easy. That is one reason why thyristors or SCRs find extremely large number of applications in rectifiers, not in inverters, not in choppers so much because with DC supply it will be very difficult for us to turn it off and inverters and choppers always have DC as the input.

Choppers convert DC to DC and inverters convert DC to AC, so if I have input as DC I will not be able to turn off the device and that is one reason why I would like not to use SCR as much as possible in DC input circuits as much as possible. We would like to use IGBTs or MOSFETs or IGCTs or GTOs and so on, those things are used more in the DC circuits not in AC input circuit.

AC input circuits generally use SCRs or diodes. So, this is the basic working of a thyristor, so if I look at the characteristics of a thyristor, the symbol of thyristor is somewhat like this, so this is exactly like a diode but there is an additional terminal. So, this is the gate terminal, this is the anode, and this is the cathode, so this is the symbol of a thyristor. So, it is exactly like a diode but with a gate, that is it.

So as far as SCR is concerned if I look at increasing the forward voltage further and further. Beyond a particular point J_2 will not be able to withstand any more voltage, at that point it will break down, so that particular voltage is known as forward break over voltage V_{FBO}, forward break over voltage. If I do not give any gate pulse also, if I increase the voltage further and further beyond the withstand capability of SCR, it will start conducting, it will breakdown.

So it will be a destructive breakdown normally, what I mean is it will not come back to normalcy, it is gone, that is it. You have overloaded it. So you will have normally this as the forward break over voltage. So normally what will happen is, it will just go like this and then it will go like this, the characteristics go like this. So it will go until the break over point, then there will be like a negative resistance characteristics which is transient which we will not be able to observe normally and then it will just take over as a normal diode.

Like as you increase the current very very slightly the forward voltage will increase, this is how it will be. Whereas on the reverse side again there will be a reverse breakdown voltage until that point it will be literally 0 current, after that if you increase it the current is going to increase, so this is reverse breakdown voltage. So on the positive side or the forward side, we call it as forward break over voltage and on the other side we call it as a reverse breakdown voltage, this is without any gate current.

If I give a gate current pulse or gate voltage, positive forward biasing of the gate this can happen at lower and lower voltage itself. So I should show it as though it happens at much lower voltage, so this happens, this will go a little bit and then it will come down drastically. Once it starts conducting immediately you are going to see that a voltage drop across the device decreases drastically.

So if I increase the gate bias, the conduction can happen even at lower and lower voltages, that is what it is indicating. If I give a gate pulse of 15 volts for example, if it starts conducting once the anode shows 100 volts, maybe if I give the gate voltage of only 10 volts, you have to increase the anode voltage to 120 volts or 125 volts, only then it will start conducting.

So you have you know the gate bias also reduces, higher the gate bias we can have the conduction started even at reduced anode voltage, less amount of anode voltage. So if I give higher and higher gate bias, I will be able to make the device conduct at lower and lower anode voltages normally. So this is essentially the VI characteristics of the SCR.

Now if I actually allow the anode current to go until let us say 10 milliamperes or 50 milliamperes and I increase the voltage further and further, anode to cathode voltage further and further, I am going to have more and more current flowing through the device. If I just allow it to go until 10 or 15 amperes and I abruptly bring down, you know I do not give the gate voltage anymore, it may not latch into conduction.

There is minimum anode current for which the device would be latched into conduction, that particular current is known as latching current. What I am trying to get that is, let us say I have a device, I have given maybe 150 volts across the device anode to cathode. I have not given any gate current, it has not started conducting. Now I am giving a gate current, I have connected a load in series with the SCR.

The current has increased to 10 milliamperes, maybe 15 milliamperes, I have removed the gate pulse. Now if I look at the current it will be 0 because it has not latched itself into conduction. I have gone to now 20 milliampere as far as the anode to cathode current is concerned. At that point even if I remove the gate pulse still the device will continue to conduct. So, at what minimum anode to cathode current the device is latched into conduction and it stays conducting even though I may remove the gate pulse, that particular current is known as the latching current.

The latching current is the minimum anode current at which the device would stay put at conducting condition even though I would remove the gate pulse, that is known as the latching current because I will require minimum amount of charge carriers to be present in all these junctions, otherwise it is not going to work that is the reason. So latching current is one of the very important parameters in thyristor. When we actually design thyristor circuits, we have to take care of this, that at least this much current flows through the device so that even if I remove the gate pulse it will continue to conduct.