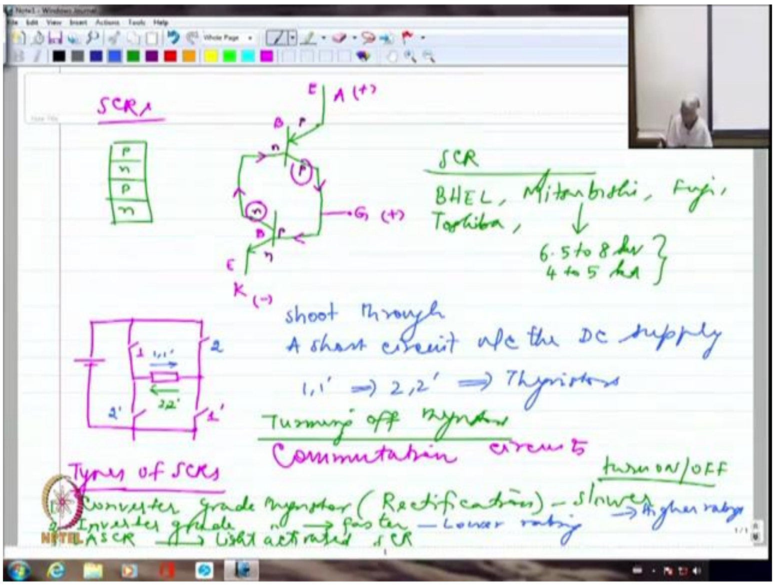
Power Electronics
Prof. G. Bhuvaneswari
Department of Electrical Engineering
Indian Institute of Technology Delhi
Lecture 3 - Power Devices: SCR, Triac, GTO and BJT

(Refer Slide Time: 00:32)



We had started on SCRs and we had also started looking at how to analyse the device. As I told you, SCRs basically are four-layered devices. So I am going to have P-N P-N. This the way it is going to be. So, which I said can be looked upon as a PNP transistor, so this is a PNP transistor which is connected to an NPN transistor. So, if I say that this is p, this is n and this is p and this is going to be NPN this particular P is connected to this P like this, and similarly this n is connected to this n like this. And we said that this is anode, this is cathode, and this is the gate terminal.

So this is the way we are going to visualize an SCR which is a four-layer device basically. So if we are looking at this these two transistors, when I am applying positive to anode and negative to cathode. You can see that this transistor we have this is the emitter, so emitter based junction is forward biased, similarly here also emitter based junction is forward biased. n is negative and p is not having any potential as such. So both these will be forward biased. But if you look at the n of the collector here either this or this, that particular junction is reverse biased because we are not applying any voltage at all. So they are going to be essentially reverse biased.

So if I apply a positive voltage here to the gate with respect to cathode, then what is going to happen is, I am pushing the gate current here. So if I am pushing a gate current here I am going to have a larger collector current as per the transistor operation because beta times Ib, β is current amplification factor, so I am going to have a large current flowing through the collector. So that is going to flow into the base of the other transistor because of which again I am going to have a larger collector current here.

So it is essentially feeding into each other and even for a very small amount of gate biased we are going to see that eventually both the transistors are driven into saturation. Both are conducting with very minimal voltage drop across themselves, that is what we mean by saturation. So, once I just give a pulse, I have already started the conduction process because of which if I remove the gate pulse no difference will it make to the device.

So, the device will be latched into conduction and I do not have to do anything to keep it still in conduction mode. So, this can be visualised as a positive point or a negative point because if I give a gate pulse and if it is latched into conduction, well and good, I do not have to give any gate signal at all. So, my gate signal circuits method, whatever is the functionality that is minimised, no problem at all, I will not have any losses and so on so forth.

But if I want to turn it off, it is not going to be easy. If I am for example talking about an inverter, I had shown this inverter earlier also when I was talking about RL load and feedback diode. So, this is an inverter circuit with a DC voltage as the input and AC voltage as the output. So, this is going to be my inverter circuit.

So if I say that this 1 and 1' corresponds to positive half cycle when the current is flowing in this direction. If I have 1 and 1' turned ON, the current is going to will flow in a particular direction. If I am going to have 2 and 2' turned ON. I am going to have the current in the opposite direction with 2 and 2 dash turned ON whereas this is going to be for 1 and 1' turned ON . But by chance if I am not able to turn OFF 1 and 1', but I have turned ON 2 and 2' inadvertently without knowing, then what will happen is both these will conduct together.

So you are looking at a dead short-circuit across the DC supply. So extremely large currents are going to flow in case I am not able to turn OFF 1 and 1' and I have turned on 2 and 2', that kind of condition is generally known as shoot through. In an inverter we call that condition as shoot through in which case I am essentially going to have a short-circuit across the supply. So, this condition is definitely a very dangerous condition because the battery is essentially like an infinite source. So, it will be able to circulate a very very large current and if these devices are not able to withstand that current they are going to conk out.

So, if I have1 and 1'and 2 and 2 'as thyristors, they are all SCRs or thyristors, then I am not going to be able to turn them OFF very easily. So, whenever I have to use a thyristor in a DC circuit with the input as DC, I have to have some additional circuits to make sure that they are turned OFF well in time. Whenever I want to turn them OFF, I have to use this additional circuitry to make sure that they are turned OFF well in time. Those additional circuitries which are meant for turning OFF the thyristors or SCRs, these are generally known as commutation circuits.

Commutation basically stands for current transfer, so I am going to transfer the current from one set of devices to the other set of devices. So, I call these circuits which are able to turn OFF one set of devices and transfer the current over to another set of devices, I call them as commutation circuit. So, if I look at actually the types of thyristors or SCRs, there are mainly three types of SCRs that are available in the market. The first and the foremost one we call them as power frequency thyristor or converter grade thyristor.

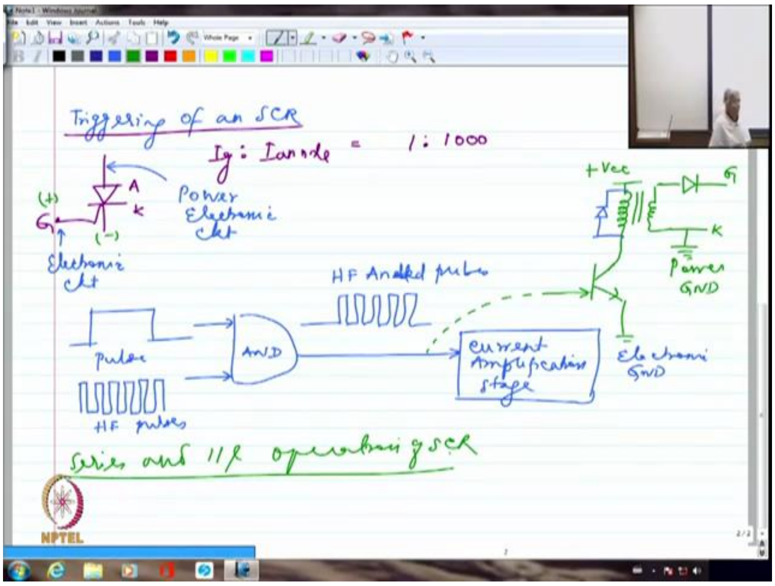
Converter grade thyristor is generally used for rectification, it is used for rectification. So, converter and rectifier again are used interchangeably, they are kind of synonymous. So, converter grade thyristors are generally used for rectifier operation. Whereas there are inverter grade thyristors, inverter grade thyristors are generally used in those circuits where I may do DC to AC conversion. So, depending upon how quickly I am going to turn ON or turn OFF the devices, I am going to get the frequency output modified accordingly. If I do 1 1' and 2 2'alternately turning ON, very quickly then the frequency of the output AC will be large. If I am doing it slowly the frequency of the output AC will be small. So, if I want to go for higher and higher frequencies, then the normal converter grade thyristors which are normally slow they are much slower.

Turning ON and turning OFF takes a longer time. So, inverter grade thyristors can be used in those places, so these will be faster normally whereas these will be generally slower. What I mean is turn ON and turn OFF, this will be generally pretty slow for the converter grade thyristor whereas it will be fast for the inverter grade thyristor. And normally we give a gate current in any of these devices to turn on. Sometimes we may use light to activate so that photoelectric effect kind of thing we will use and that will emit some electrons because of which I will have the conduction possible. So, the third one is LASCR, LASCR is light activated silicon-controlled rectifier. So LASCR is those devices will be activated basically by light, so these are light activated SCRs. So, these are mainly the three types of devices that are available in the market if you go under the category of SCR.

So if you actually look at the ratings, SCR ratings are really large that are available in the market are very very large. In fact there are some companies, in fact our BHEL produces some SCR and Mitsubishi produces, Fuji, Toshiba, Infineon Technologies all these things international rectifiers in USA, all these things produce, SCRs. And Mitsubishi generally has a very very high rating, so also is Infineon. Mitsubishi rating is of the order of about 6.5 to 8 kilovolts along with about 4 to 5 kiloamperes, very large rated SCRs are available from Mitsubishi.

But mostly the highest-grade SCR, highest power rated SCR will be converter grade. Inverter grade because they have to be turned ON and turned OFF very quickly which means huge number of charge carriers, they have to be stepped out. It takes longer. Generally, inverter grade thyristors will be available only at lower rating, this may be available only at lower ratings. Whereas this will be available at higher ratings. So, these are some of the characteristics of thyristors when we look at the different types.

(Refer Slide Time: 12:19)



Now let us try to take a look at how to fire a thyristor or to how to trigger a thyristor. How are we going to trigger an SCR? What we mean by triggering or firing is we are going to turn it ON, from OFF condition it is going to be pushed into ON condition, that is what we are trying to do. So invariably thyristor by the way the symbol is somewhat like this, I am going to have anode here, cathode here and gate terminal is generally specified like this.

So to this gate I will have to give a small amount of positive bias, then it would be able to conduct. But if I look at the current amplification in this case, I_g versus I anode, if I try to look at it, generally in an SCR it is 1 is to 1000 or more. So if it is like 1000 ampere thyristor, 1 ampere of current would do in the gate for it to be triggered.

So obviously, the circuit that is connected here is going to be microelectronic circuit, whereas what is connected here will be power electronic circuit or high-power circuit. So, as I told you earlier it is essential for us to have isolation between microelectronic circuit and power electronic circuit because if something goes wrong in the power side, huge amount of current will flow into electronic side and it will not be able to withstand. So normally the grounds will be isolated. The grounds will not be connected together.

So how do we really, isolate the ground of the SCR gate versus anode? That is what we will have to check. Let us say I have probably gotten some pulse. Something like this, this is the pulse that I want to give to the thyristor. If I give a pulse directly and if I am planning to use a transformer for isolation, then the transformer will saturate, transformer is not supposed to carry DC. If I am trying to isolate the gate circuit with that of anode circuit with the help of a transformer, I would like to convert this pulse into, some kind of smaller duration pulses, so what we can think of is like a clock in your computer or microprocessor I can have a clock and this high-frequency pulse and the normal pulse both of them can be given to an AND circuit AND gate.

So if I do that, whenever I am going to have this pulse I am going to get essentially the output of this to be all here, it will be zero and then I am going to have some pulses like this. This will be the output of the high-frequency and dead circuits. So, this now if I can give it to a transformer, in all probability that transformer will not saturate provided I give ample time here for de-fluxing or whatever is the flux that has been accumulated in the transformer winding it should have enough sufficient time to kind of, get rid of that flux.

So this particular thing, whatever is the high-frequency, so this is HF pulses and this is HF and dead pulses. So high-frequency and dead pulse, now this may be only of 5 volts and few microamperes in all probability. If it is 1000 ampere thyristor, I said that I will need 1 ampere to fire it, so I need to amplify it. So there has to be a current amplification circuit in between. So whatever is the output here, this goes to current amplification stage.

So the current amplification stage can be a simple common emitter amplifier like what you have seen in transistor. But we will have to have a current amplification stage. So this current amplification stage normally will be an NPN transistor, so whatever is this signal this we are going to give it to the gate and here is my transistor. So, I can imagine as though the transformer is here.

The transformer primary I have shown, and I necessarily must have another secondary. So, if we have seen big transformer in terms of mega volt ampere and so on, this will be 1 volt ampere or maybe maximum 10 volt ampere, that is it, nothing more than that. It is going to be a very very small sized transformer, it will still be iron cored normally. It will be an iron cored transformer, and generally, gate has to get positive and cathode has to get negative when I am giving the gate pulses.

So generally if I say that this is my V_{cc} which is actually plus, obviously this corresponds to minus. So this will go to cathode and in all probability I may put a diode as well to make sure that no negative pulses go into the gate because it can be detrimental to the gate. So we will normally have a diode and here is where I will have the gate current. And here when I am having the current during the pulse being in high stage, the current cannot be abruptly brought down to 0. So normally, I may have a freewheeling diode here, there will be a freewheeling diode here. So, so much so for the triggering circuit of a thyristor or SCR. So you are starting from the pulses, you normally AND it with high-frequency to make sure that the transformer which I am going to use here does not saturate.

After high-frequency AND-ing, I necessarily need to amplify it because in all probability SCR will require a higher current. So, this amplification stage itself will have the pulse transformer connected in the collector of the transistor so that I have complete isolation. Please note that this cathode if I call it as the ground of the power circuit, here is the ground of the electronic circuit. This ground will be the same as that of the pulses ground and circuit ground and so on and so forth.

The electronic ground is here. So, this is electronic ground whereas this will be power ground. So, the two grounds will be completely isolated from each other and I am able to give this kind of an isolation with a transformer because it is an SCR. Once I give a pulse it will start conducting. So even if I bring down the voltage, still it will continue to conduct, it is not going to shy away from conducting, that is the major advantage of having an SCR and we can have basically isolation with the help of a transformer which we will see eventually that in BJTs or MOSFETs or IGBTs, we will not be able to do because there if you give a base pulse, the base pulse has to be in high condition continuously for the device to conduct.

If the base pulse is in not in high condition it will come from ON state to OFF state. And we do not want in all probability our device to go from on state to OFF state. Most of the time we fire it with multiple number of pulses because by chance if it does not fire here it can at least fire here. By chance if it misses these two, it can at least fire in the third and so on, ok. Because invariably SCRs are used with AC supply and at what point really the alternating current goes from the positive half cycle to negative half cycle or negative half cycle to positive half cycle, we may not be sure.

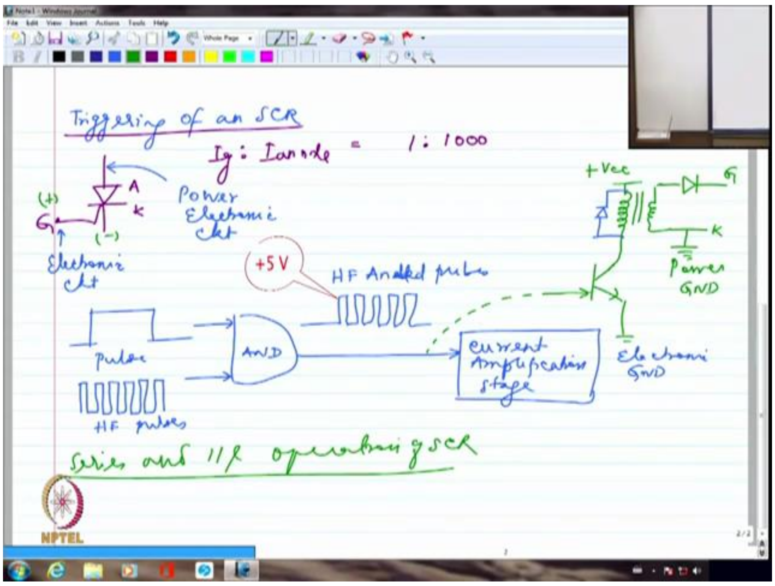
So we want to make sure that we give it ample chance for conduction, that is the reason why we will repeatedly give the pulses so that we give it ample chance to get into conduction. So SCRs if I look at, triggering is pretty simple, it is not to involve because all you need is a high-frequency ANDing and another amplifier and a pulse transformer, nothing more than that.

But commutation is going to be a little more difficult but before that we will also look at series and parallel operation. I do not think I need to really expand upon that much because we have already seen for diode. A similar situation happens for SCRs also. So series and parallel operation of SCR is very common.

Student: Is it creating this current amplification circuit?

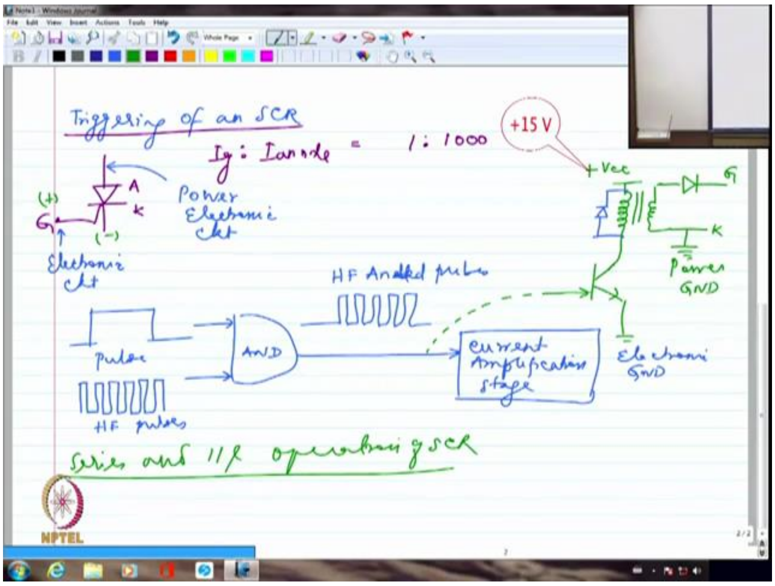
Professor: See, you are not doing the power amplification, this is even power amplifier. I should not say only current amplification.

(Refer Slide Time: 23:09)



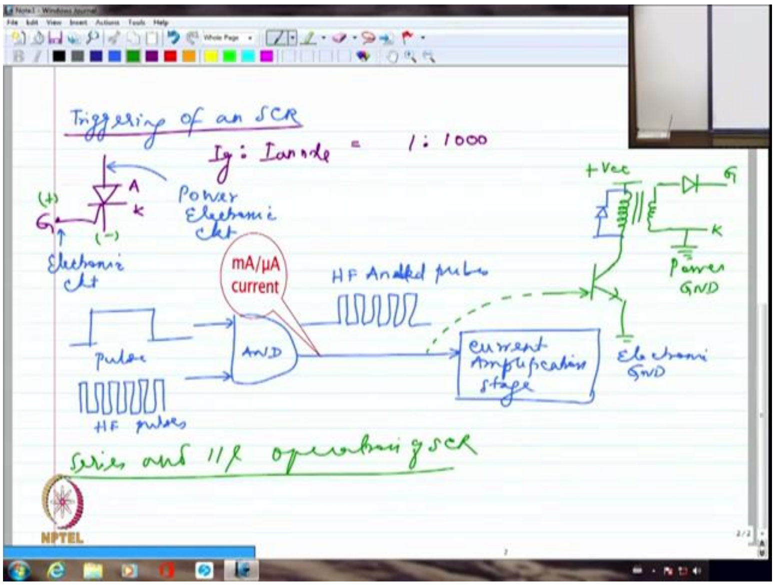
It is actually power amplifier because what I get from here maybe 5 volts.

(Refer Slide Time: 23:12)



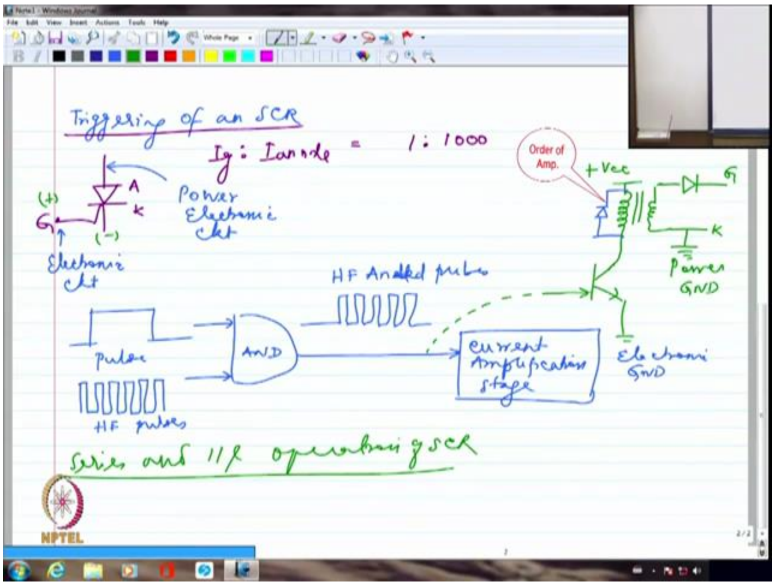
And what I get from here maybe 15 volts.

(Refer Slide Time: 23:14)



And what I get from here maybe milliamperes or microampere.

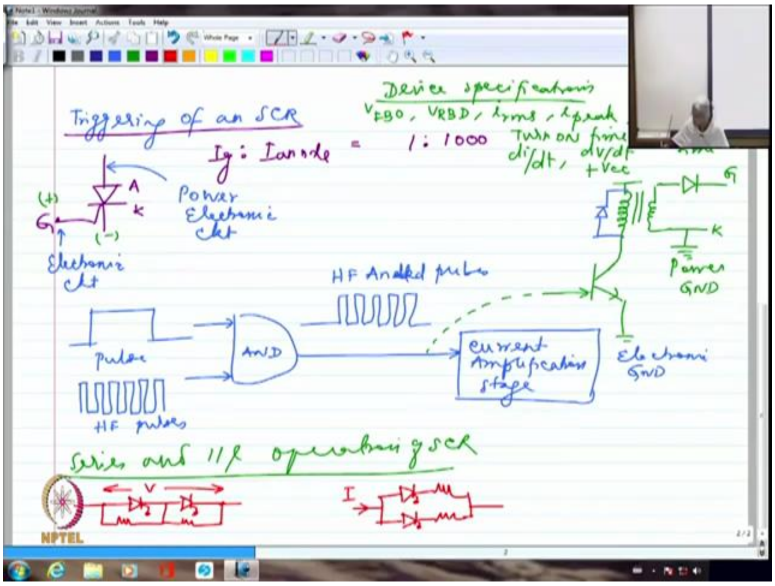
(Refer Slide Time: 23:19)



But what I get from here will be of the order of amperes. So I am not only amplifying only the current I am also amplifying the overall power. And for that I am drawing the power from VCC. So VCC is supplying the power for me to amplify the current pulse. Whereas in this case if I just use a transformer either you will amplify the voltage or you will amplify the current. You cannot amplify the power, the power is invariant. From the primary side to secondary side.

So that is the reason why we use the transformer only for isolation not for amplification.

(Refer Slide Time: 24:08)



Forward biasing voltage and the gate current, both will be specified for a device. In fact, if I look at the device specification, normally if I just say how the device specifications are given? Normally what they will give is the forward blocking voltage, how much voltage it can block in the forward condition.

The second thing they will give is what is the reverse breakdown voltage. And again even in the reverse breakdown voltage there will be two different kinds of categories they will give. Normal reverse breakdown voltage and repeated reverse breakdown voltage. If I just apply only one 7 kilovolts, this device may be able to withstand. But if I repeatedly apply 7 kilovolts, it may conk out because I am putting it under stress repeatedly, so it will conk out.

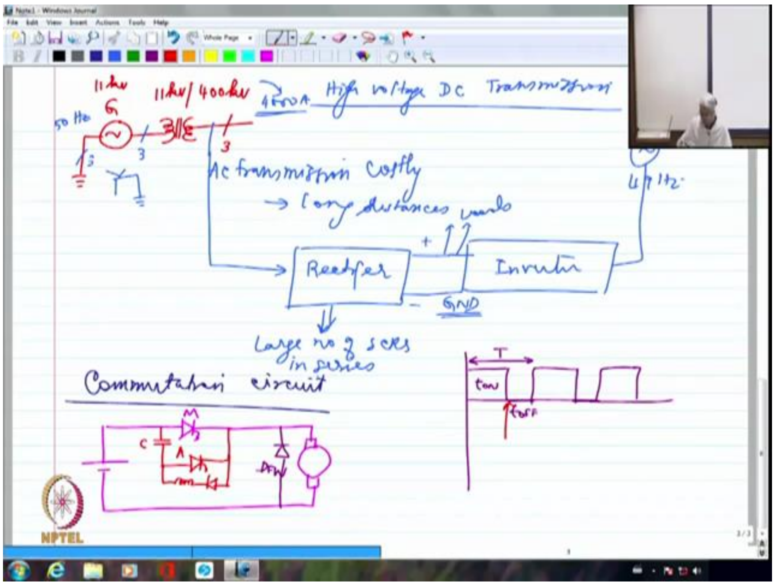
So repeated reverse voltage and just once a reverse voltage or a peak reverse voltage that I can subject it to. So these are the two categories normally they will give. Then apart from that they will also give what is I_{rms} it can withstand, then they will give i peak it can withstand any device right? And then they will say what is V_{gk} that is needed for triggering the device, then apart from that they will also say how much is Ig? How much is the gate current that is needed? Then there is one more thing which will be coming out as turn on time, how long it takes for the device to come into ON condition? After I give the gate pulse does it immediately come on or does it take a little longer? So that is turn on time.

Then there is also be turn off time because turn off is not easy, we are going to look at that also but turn off is going to be difficult. So, which means if a recombination takes 50 microsecond, 100 microsecond, am I enabling the device to completely recombine? So that is essentially specifying what is the turn OFF time. Apart from that they will also give what is $\frac{di}{dt}$ and $\frac{dv}{dt}$ the device can withstand.

How much is the $\frac{di}{dt}$ the device can withstand? If I try to go beyond that, the device might breakdown. Similarly, $\frac{dv}{dt}$; because while turning ON, I am going to have from a large voltage it will come down to 0 voltage or very low voltage. Similarly, when I am turning OFF it will go from a very small voltage suddenly to a large voltage. So in both the cases it should be able to withstand. So $\frac{dv}{dt}$ limits are generally given.

And as we have done in series and parallel operation of the diode, here also I can have series operation of thyristor like this with large resistances in parallel. Similarly, parallel operation I can do for two thyristors with small resistances in series. When I want to share a larger current I. Here it is sharing a larger voltage V among the two devices. Now this is very commonly used in high voltage DC transmission systems. I do not know whether you have heard of high-voltage DC transmission system.

(Refer Slide Time: 28:23)



In high voltage DC transmission system what happen is if I am having a generator, I am just showing this as though it is a single-phase generator, we call it as single line diagram. It is three-phase, but I will show only one line at a time. Every line indicates three-phases basically. So this is my generator and I am going to have basically a transformer which we will step up, maybe the generator will generate only 11 kV or 12 kV or whatever. From this it is going to be generally stepped up to 400 KV.

The transmission voltages are very large because we want to bring down the current. For the same power we want to bring down the current. But the generator has a limitation of what is the maximum voltage it can withstand, otherwise you are going to have very thick insulation inside the machine. And in all probability, I will not be able to put such thick insulation inside the machine, that is the reason why we are having 11 kV or smaller sometimes we will go up till 20 kV, nothing more than that.

So, there is a limitation of generating voltages because of the insulation that is being used in the machine. Whereas the transmission voltages are generally chosen to be much higher because I would like to bring down the current, that is the reason. So, this has now brought down the current and then from here it is going to get distributed, transmitted and distributed all over the country for example.

But when I distribute it or transmit it, these are three conductors, please note all these are at least three conductors. And apart from that I may have a neutral also because if it is actually the generator star connected, I may ground the neutral as well. So, I will have four conductors coming out normally. So, if I have four conductors coming out and when I have 2000 kilometres being spanned maybe from north-east region to Gujarat, so obviously I will have four conductors going all the way through this 2000 kilometres which is definitely going to be extremely costly. So, I cannot afford to always have AC transmission.

AC transmission comes in handy because of the transformer. It can step up and step down the voltages which is very very good, that is the reason why Tesla won the war of power. When you compare Edison and Tesla, Edison actually lost the war of electricity or power because he was always arguing for DC whereas Tesla was arguing for AC and Tesla was hired by Westinghouse. And Westinghouse is the one who ventured into AC transmission.

So, this AC transmission becomes costly when I am talking about long distances. So now that we have rectifiers and so on and so forth everything is available with the power electronics converters. So, what is being done normally is whatever is available in the form of three-phase, this is actually connected to a rectifier. And a rectifier obviously has to withstand $400 \times \sqrt{2}$ kV.

Because 400 kV is rms, so $400 \times \sqrt{2}$,each of the devices have to withstand. And I have to put a factor of safety in all probability 1.25 or 1.2, so it is going to be way too high. There are no devices available for 400 kV $\times \sqrt{2} \times 1.2$ or whatever, that is not going to be possible. So we use lot of thyristors in series, normally that is what we do.

So whenever I am talking about this rectifier, this is going to essentially use large number of SCRs in series. This is going to have large number of SCRs in series. Now the rectifier has rectified the voltage, so I am going to have a plus and I am going to have a minus. Now there are only two conductors, I can take it to extremely large distances, I will save on copper, instead of four conductors RYB and neutral now I have two conductors,

In fact in some of the cases this will be, return will be ground. In some cases return may be ground which means I have only one conductor. So compared to 4 conductors if I can bring down the cost by using only one conductor, obviously it makes better sense. So that is the reason why many of the large distance transmissions now are being thought about to be done with HVDC (High-voltage DC) transmission.

So high-voltage DC transmission is applied in many of the cases where I have to transfer electricity over very long distances so that I will be able to save on copper, that is one advantage and other advantage is let us say I have 50 Hz here. Maybe I want to tight up to some other system which is having maybe 49 Hz on the other side. So, I will have an inverter here, an inverter I can fire at my own will and wish, not a problem. Fire it at 49 Hz work is done.

So I can directly connect this to the 49 Hz source and in between of course I may have several loads connected. Many loads may be connected directly to the DC, maybe to AC and so on and so forth. So high voltage DC transmission systems invariably use light activated SCRs. They use light activated SCRs because light definitely is no way connected to the electricity, I do not have to worry so much about isolation and so on. And it is a very very high voltage and high power device.

So inherently if there is isolation, nothing like it. So I may use several LASCRs in series, I may not have to use them in parallel because I may have 400 kV and maybe 4000 amperes, that is good enough or 2000 amperes. And one SCR can carry very easily 2000 ampere not a problem. So most of the time what we see in HVDC transmission system is series connected SCRs, hardly ever we see parallel connected SCRs.

So we will have rectifier, for every device in the rectifier there will be a string of SCRs. Many of them are connected in series, of course with parallel resistances, protection system, so SCR will be only this much but all the paraphernalia which is adding will be too big generally and the heat sink and so on and so forth. So many things will be there. So this is typically the case when we talk about series operation and parallel operation of SCRs.

Now let us go over to the commutation circuit. What you mean by commutation is, to turn OFF an SCR circuit. How are we going to turn OFF a circuit? I am going to take an example and explain it so that you will be able to get an idea of how an SCR is turned OFF. So, let us say I have a chopper circuit, again that is one of the simplest circuits. So, I am going to take a chopper, I am having an SCR and I am calling this as main SCR M. And this is connected to the DC motor drive, maybe I am going to feed a DC motor drive with a chopper, the chopper consists of basically a switch nothing more than that a DC voltage source and a switch.

Now I am going to have a freewheeling diode, of course this we already said it is essential if you do not have a freewheeling diode it is going to be a problem because the current will be abruptly interrupted, $L\frac{di}{dt}$ will be very large, thyristor will be conk out. So, I do not want that to be happen. And motor by default will have some inductance, cannot help it. So that is the reason why I am putting a freewheeling diode, so this is a freewheeling diode.

When I turn on this main thyristor or main SCR, I am going to have the power supply given to my motor but I would like to turn it OFF after sometimes so that the average voltage becomes less. I want to have control over the voltage. That is why I am employing a switch, so I want probably this to be ON for some time, OFF for some time, again ON for some time, OFF for some time and so on, this is how it is going to be.

So this is t_{ON} and this is going to be t_{OFF}. And this entire thing is going to be the period of the chopper T, this is how it is going to be. So the average value of voltage I told you already that whatever is the ON-time correspondingly it is going to have $\frac{t_{ON}}{T}$. So multiplied by the applied voltage, that is going to be the average voltage. This is how it is going to be.

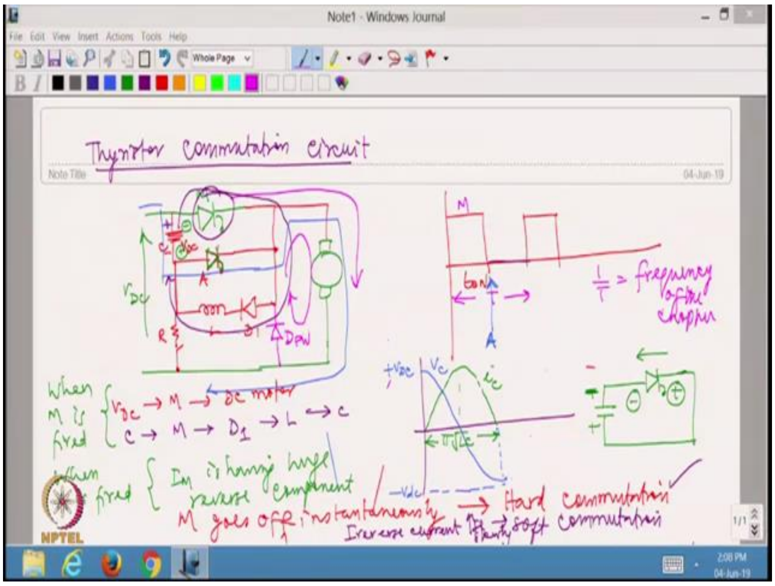
So, I have to turn this OFF at this point. If I do not turn it OFF at this point it is going to be difficult. I cannot really get the average voltage to be less than whatever is the input voltage. So, to turn it OFF, had it been a transistor or something I could have just removed the base drive, if I remove the base drive it will go off simply. Whether it is FET or whatever it is, the moment I remove the drive it will go OFF.

But in this case, it is not going to be OFF. We said that once those two transistors are driven into the conduction they will not come back, that is the problem. So, for that we have to have some auxiliary circuits which are known as commutation circuit. A typical commutation circuit

I am going to show. So these are all part of commutation circuit what I am showing in the red, so many things, this is capacitor, this is an auxiliary thyristor then I am going to have an inductor and I am going to have a diode and so on and so forth.

So many things are added to make sure that this particular device goes OFF. So, whatever I have shown in red, the entire thing correspond to commutation circuit, that corresponds to commutation circuit. So, let me try to explain how this works.

(Refer Slide Time: 40:28)



As I have told you earlier the main thyristor M is actually going to give the power to the DC motor drive, and it has to be turned OFF at the end of t_{ON}. So, if I talk about the entire thing as a chopper circuit which is feeding the DC motor drive. For t_{ON} it is going to be ON and for rest of the period it is going to be OFF. Again, for t_{ON} it is going to be ON and so on. So, this entire period is the period of the chopper.

So $\frac{1}{T}$ is equal to f which is the frequency of the chopper. So, I am going to have M fired at this point and whenever I want to turn M OFF, I am going to fire the auxiliary thyristor at this point. As I told you all that is drawn in this red colour, all these things are part of commutation circuit, this is the capacitance C. Now let us say the capacitance is already pre-charged to a voltage like this.

This could have been done by having an auxiliary resistor and a switch which can be closed for a short while until the capacitance charges to this plus and minus with V_{DC} the voltage is V_{DC} currently. Now whenever I want to turn ON M, turn OFF M, I am going to fire A. So, the moment I fire A there are two currents that will be flowing through M. One is directly from DC source through M to the DC motor, this is one of the currents.

And the second current is going to be the capacitance itself is going to discharge, so you can look at discharging path somewhat like this, this is going to be the discharging path. So, I will have C then M then I am going to have the diode D_1 then I am going to have inductance L back to C. So, if I assume that L and C are ideal, it is going to have an oscillation LC oscillation through the circuit.

So, if I try to look at the voltage, I am going to actually see that the voltage will reverse like this. It is starting from plus V_{DC} and it will go to minus V_{DC}. So, this is essentially the capacitor voltage, so V_C I am drawing like this. At the same time if I try to look at that current, the current would have reached the peak when the voltage is actually at the zero point. And it is going to reach zero when the voltage is at the negative peak point that is when it is at negative peak. So this is going to be the capacitance current waveform or it is same as the diode current waveform.

So this oscillation time will be equal to $\pi\sqrt{LC},$ all of this definitely. In the LC circuit, $\pi\sqrt{LC}$ is going to be the half cycle time. So within $\pi\sqrt{LC}$ this would have reversed its charge. So you would see that now this has become plus and this has become minus. The moment I am going to have this has become plus and this has become minus, now this is ready to commutate the main thyristor at any point in time.

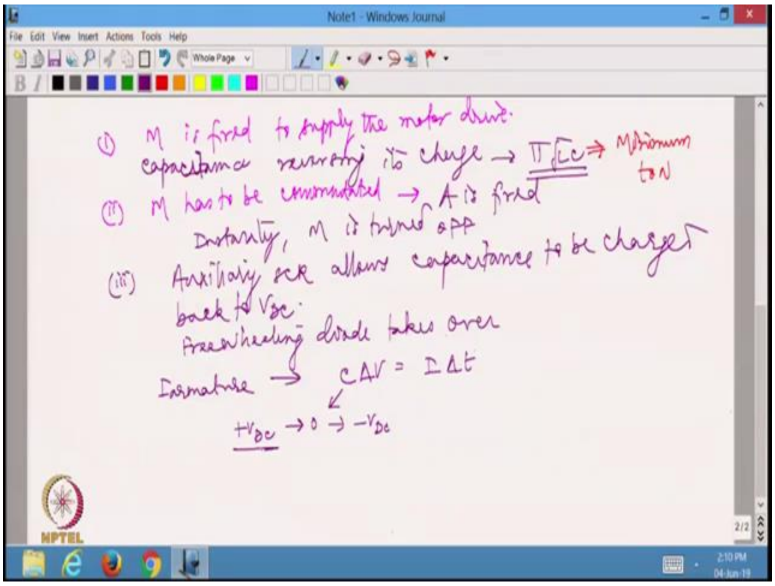
So I am going to now fire this auxiliary thyristor, so this is essentially when M is fired whereas when A is fired after $\pi\sqrt{LC}$ elapsed from M or even more than that. At that point I am going to have essentially a circuit somewhat like this, this is the capacitor which is having plus here and minus here. This is minus and I am having main thyristor here and I have an auxiliary thyristor which is working like a short-circuit.

You can very clearly see that the plus is connected here, and the minus is connected here which is going to force a huge current in the opposite direction. The resistance is literally negligible because the current is having huge reverse component. So essentially that cannot be allowed by the thyristor, so M is going to go OFF, so M goes OFF instantaneously. So, you can say because M goes OFF instantaneously, we call this as hard commutation.

If you are allowing the reverse current to rise slowly, then you will call that as soft commutation. Soft commutation is such a case where you are going to make the reverse current rise slowly if I allow reverse current to rise slowly. In that case we will call it as soft commutation but this is very clearly hard commutation. Once the commutation takes place, this M is not going to conduct anymore, when M is not conducting anymore now the path for the current will be through the capacitance like this through the auxiliary thyristor and through the freewheeling diode through the DC motor drive like this.

That will happen until the capacitance charges to plus and minus like this fully to V_{DC}. After which the capacitance will act like an open circuit, so now the freewheeling diode will take place. I can actually say freewheeling diode should have been there in the circuit because DC motor has some amount of inductance, now you can see that current will flow like this, it is just freewheeling.

(Refer Slide Time: 46:46)

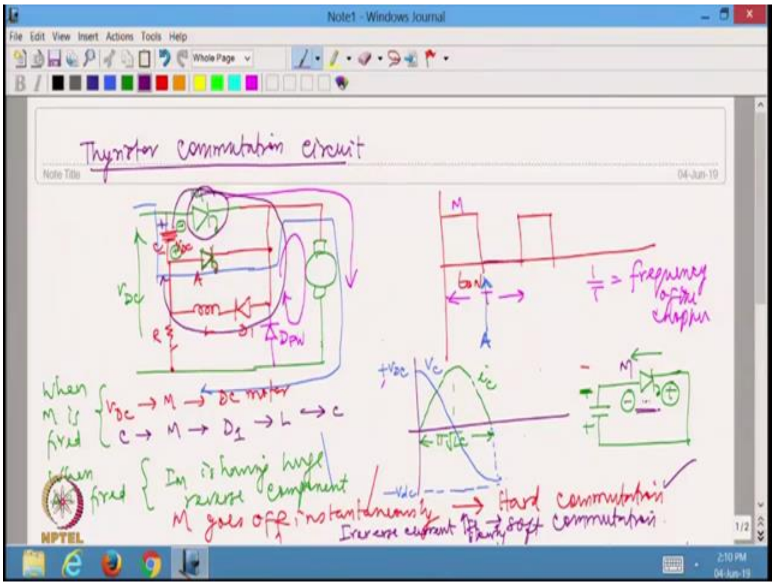


So in this particular case you can see there are totally three modes. One is first when M is fired to supply the motor drive. Simultaneously you are going to have the capacitance reversing its charge, which means this will need is at least $\pi\sqrt{LC}$ as the time that is needed for the main thyristor to be ON. So this is the minimum on time. I cannot have less on time than this this is the minimum on time.

The second portion is when M has to be commutated or turned OFF, under that condition I am essentially going to fire A, when A is fired, I am going to have essentially instantaneously. Instantly I am going to have M is turned OFF because of very high current flowing in the opposite direction. And after this I am going to see that auxiliary thyristor that is the auxiliary SCR allows capacitance to be charged back to V_{DC}, so it will be ready for the next cycle of operation, after this freewheeling diode takes over.

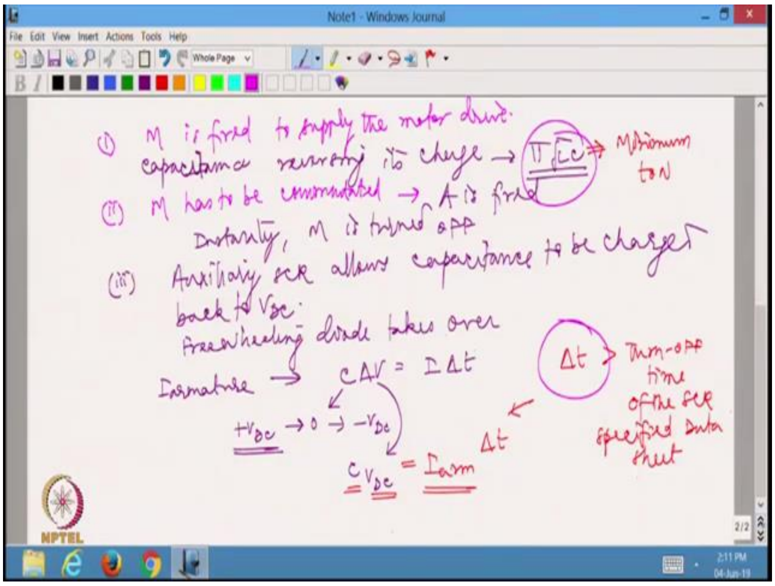
So basically, the circuit is designed based on two things one is, this minimum t_{ON} which is $\pi\sqrt{LC}$ and another one is you are going to have basically I load or I armature of the DC motor might have been given already, this is the load condition. So you can say $C\Delta V = I\Delta t$ .And if I actually look at it the capacitance voltage is literally going from $+V_{DC}$ to 0 to $-V_{DC}$, this is how it is transferring.

(Refer Slide Time: 49:15)



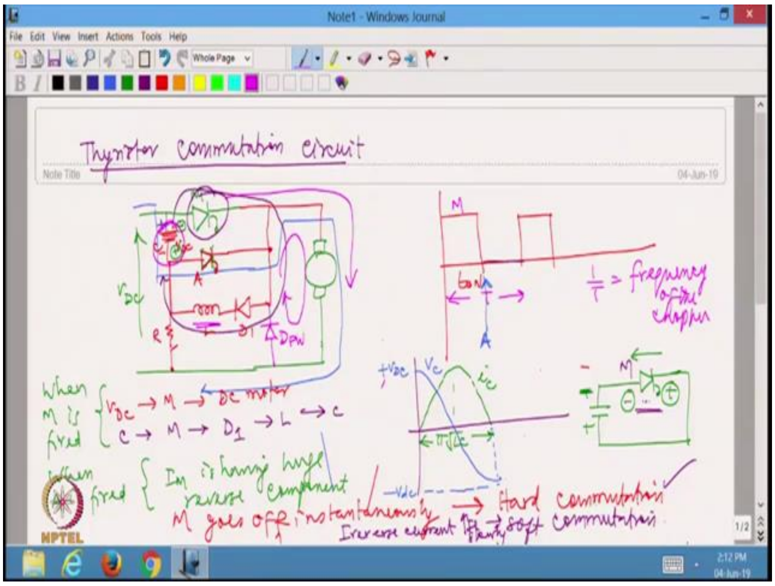
So which means whenever it is actually having the voltage with the polarity plus here and minus here, then this main thyristor is going to be reverse biased. Only if it is reverse biased it is going to be turned OFF properly. So how long will it be reverse biased? Until this voltage becomes zero.

(Refer Slide Time: 49:32)



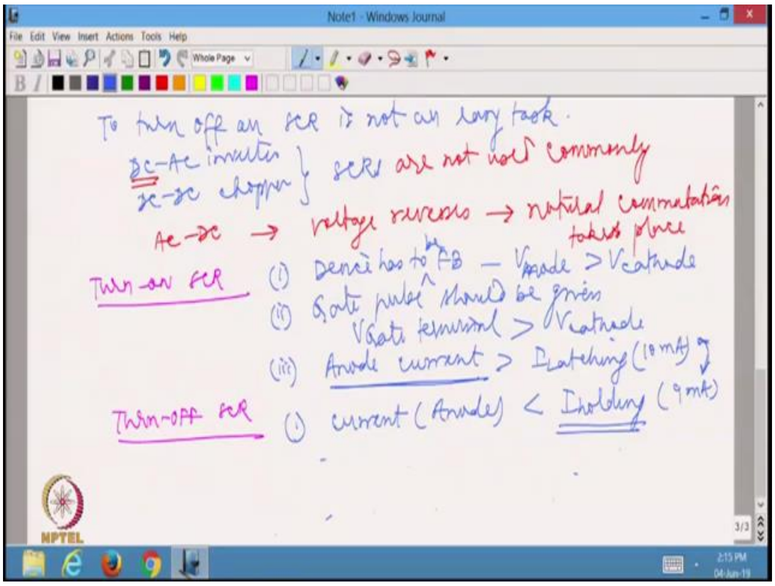
So I can say ΔV in this case happens to be V_{DC}, C is the capacitance value and I am going to have I as the armature current, whatever is the armature current multiplied by Δt. So how long does it take to reverse is governed by the capacitance, what is the DC voltage and what is the load current. This Δt has to be greater than the turn OFF time which is the recombination time for the charge carriers to recombine, so this turn OFF time it has to be greater than the turn OFF time of the SCR which is specified in the datasheet, this will be specified normally in the datasheet. So you usually need 2 conditions, one condition has to be this Δt constraint, the other condition is $\pi\sqrt{LC}$ constraint.

(Refer Slide Time: 50:31)



These two together you should able to design, this entire L, C and so on. So this is a typical commutation circuit which is used for turning OFF an SCR.

(Refer Slide Time: 50:44)



So that to turn OFF an SCR is not an easy task. You will require a major auxiliary circuit for this, that is one reason why in DC-AC inverters circuits as well as DC-DC chopper circuits generally SCRs are not commonly used because input excitation is DC, so never are you going to reverse bias the SCRs very easily naturally. So SCRs are not used commonly in these two circuits because it is not going to easy to turn them OFF.

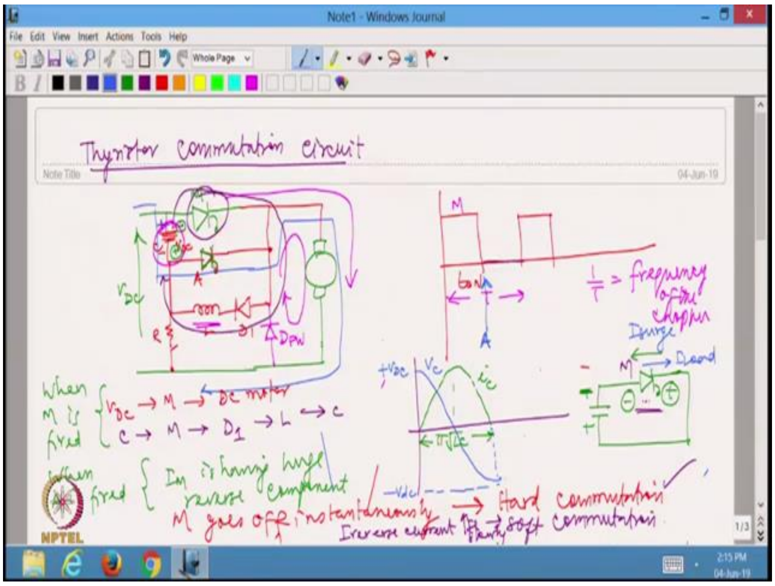
Whereas if it is AC-DC circuit and so on, automatically the voltage will reverse, the source voltage will reverse because of which commutation or natural turn OFF or natural commutation will take place. So it is always good to use SCR in AC excited circuit not good to use them in DC excited circuit. So if we summarise the turning ON of the SCR mainly requires a few conditions to be followed.

First the device has to be forward bias which means I am going to have V at anode is going to be greater than V at cathode. Voltage at cathode will be less than voltage at anode. The second condition is gate pulse should be given which means gate terminal is at a higher potential, this potential will be higher as compared to cathode potential. The third condition is even after these are done, the current that is the current flowing through the device has to be greater than the latching current of the device.

The latching current essentially gets that name because the device will be latched into conduction only if the current is greater than the latching current. These are the three conditions for the turn ON of the SCR.

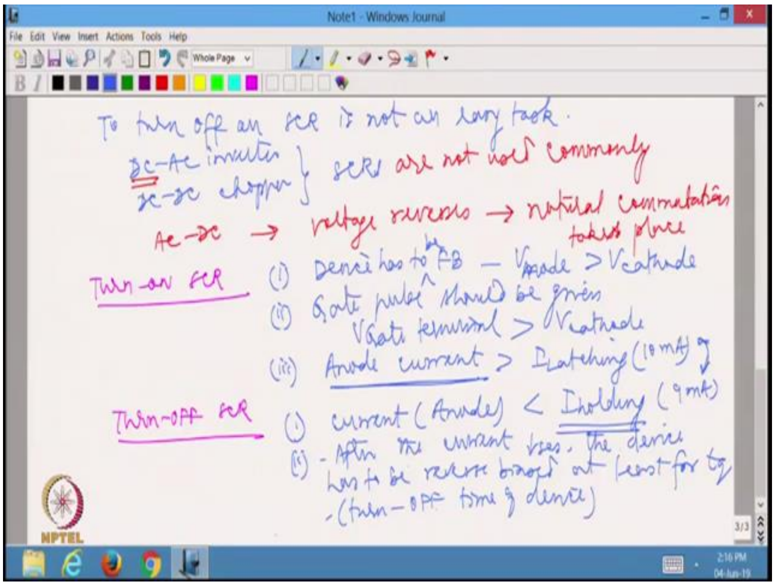
For turning off the SCR at least two conditions have to be followed, the first condition is the current through the device that is the anode current I am talking about, has to be less than the holding current. If I say latching current is somewhere about 10 milliampere, holding current will be somewhere around 9 milliampere. They will be very close to each other, there will be hardly any difference. But the anode current first of all has to be decreased to your value which is less than the holding current.

(Refer Slide Time: 53:44)



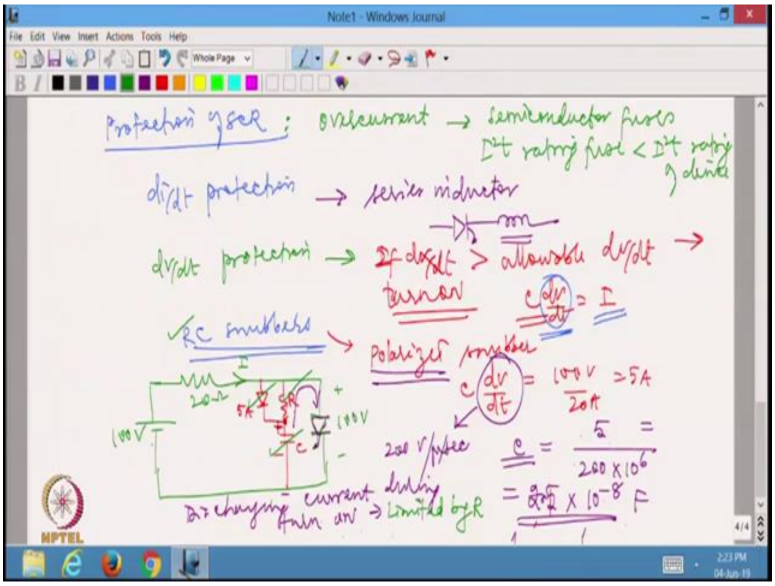
Please note that is what happens in this commutation circuit case. Originally the current that was flowing was the load current. Now whatever is the current that is flowing in reverse direction is the surge current due to the capacitor, this I surge basically. This is going to be I surge. So this I surge will be definitely higher than I load, so overall current becomes negative.

(Refer Slide Time: 54:11)



So the first condition to be followed is the current has to be less than holding current maybe negative direction. The second condition is after the current decreases. We have to reverse bias the device has to be reverse biased at least for turn OFF time. So at least for t_q, t_q is the turn off time of the device specified in the datasheet. Turn OFF time of the device which is specified in the datasheet. So, these so much for SCRs.

(Refer Slide Time: 55: 02)



Now we have still not talked about protection of SCR. So, SCRs are generally slower devices, so it should not be too difficult to protect them. Against overcurrent if you want to protect them normally semiconductor fuses are used. Semiconductor fuses will be melting before the device conks off. So I^2 t rating of the fuse basically has to be smaller as compared to I^2t rating of the device. What I mean is the heat generated in the fuse will melt it much more as compared to whatever is the heat generated actually in the device, so the device will not conk out.

The second thing is $\frac{di}{dt}$ protection, $\frac{di}{dt}$ protection is generally done by having a series inductor. The inductor will never allow the current to rise right away. So normally if this is my device in series with that I will put a small inductance, so this will make sure that the current does not increase untowardly.

The third one is $\frac{dv}{dt}$ protection. If the $\frac{dv}{dt}$ goes beyond a particular value. If $\frac{dv}{dt}$ is greater than whatever is the allowable $\frac{dv}{dt}$ of the device then the device can turn ON. So the turn ON can happen even due to this. After all when you apply a large rate of rise of voltage, C $\frac{dv}{dt}$ is generally I. So any junction capacitance can be represented by the C. So if by chance $\frac{dv}{dt}$ is much larger the current that is passing through any of the junctions can go way beyond the limit which will automatically make the device on.

So you do not want spurious turn ON of the device, that is the reason why $\frac{dv}{dt}$ has to be within the limit. So generally RC snubbers are used for protecting the devices against spurious $\frac{dv}{dt}$ turn OFF. Let us take a typical circuit, let us say I have probably voltage source maybe 100 volts or something. Let us say I have 20 Ω resistance. And I am going to have a thyristor here.

And it is going to be turn ON and OFF, I am not really showing the gating circuit or I am not showing the commutation circuit. When this is turned OFF entire 100 volts will come across the SCR. So if I try to look at the voltage, this will be plus and minus and 100 volts will come across the device if the current is going to be zero. If I is flowing then there is no problem, if I is equal to 0, I will get the entire 100 volts right away. This can actually turn on the device spuriously; it will not go off at all.

Just to prevent this, what I can do is to connect an RC circuit, normally a diode is also connected here. When a diode is also connected it is called polarised snubber. So during this condition what happens is, I am going to have essentially this 5 ampere flowing through the diode to charge the capacitance. So the capacitance is going to get charged with plus here and minus at the bottom.

So this is R, this is C but R does not have any role to play right now. So I am going to have

$$C\frac{dV}{dt} = I = \frac{100}{20} = 5A$$

Let us say this $\frac{dV}{dt}$ which can be withstood by the device is 200 volts per microsecond, I am just arbitrarily taking the value. So I will have C equal to 5 ampere divided by 200 into 10 power 6.

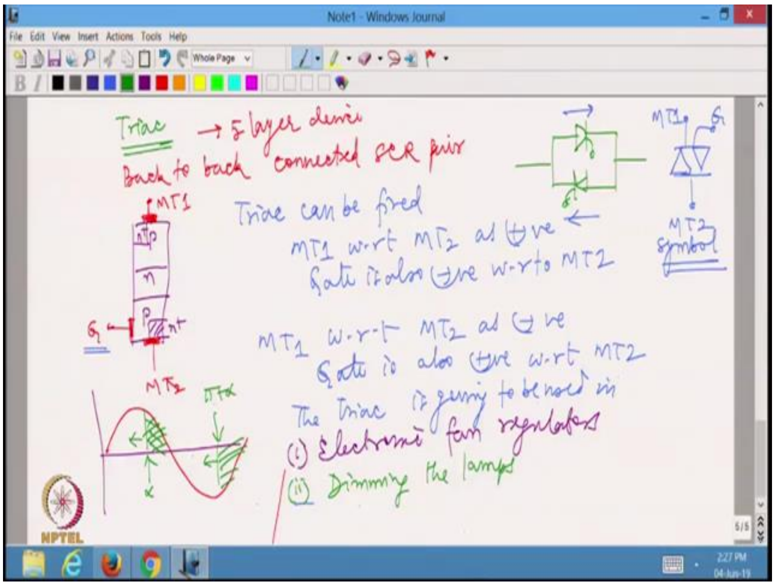
$$C = \frac{5}{200 \times 10^6} = 2.5 \times 10^{-8}F$$

So that means 0.0025 micro Farad that is what I am going to get. So if I choose a capacitance which is of the order of this particular capacitance value, I will make sure that the voltage across the SCR is not exceeding $\frac{dv}{dt}$ limit that is given by the datasheet.

So, RC snubber or polarised snubber helps me to make sure that the capacitance is not gaining the voltage at a very fast rate. The capacitance is right across my thyristor, so thyristor will also not have a huge $\frac{dv}{dt}$. But what is the role of this resistance? That's what we will have to check also. I have turned off the SCR, now if I am going to turn on the SCR please note the capacitance will try to discharge through the SCR.

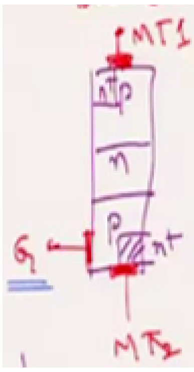
If I do not have a resistance the current that will be flowing through the SCR although it is in the correct direction it is flowing from anode to cathode, this is going to exceed the limit. The I value will become extremely high, so discharging current during turn ON. That is limited. This is limited by R, so I have the function of diode spelt out I have the function of R spelt out and capacitance spelt out, so this is essentially talking about RC snubber. So with this we are kind of concluding our discussion on SCR.

(Refer Slide Time: 61:42)



Now the next device which is related to SCR which I want to take up is Triac. Triac is basically a five-layer device and it is equivalent to a back-to-back connected thyristor or SCR pair. What I mean by back-to-back connected SCR pair is, I will have one thyristor connected like this, another thyristor connected like this and they are connected in antiparallel. So Triac is exactly equivalent to this.

Let me draw the symbol of Triac, the Triac symbol is somewhat like this.



I am going to have one triangle like this, one more triangle like this and I am going to have a gate terminal. So one of them is specified as MT1, the other one is specified as MT2. There is no point in telling this as anode and cathode because the current can either flow this way or flow this way, so there is no point in telling that this is the gate terminal. So this is the symbol of Triac, this is going to be the symbol of Triac.

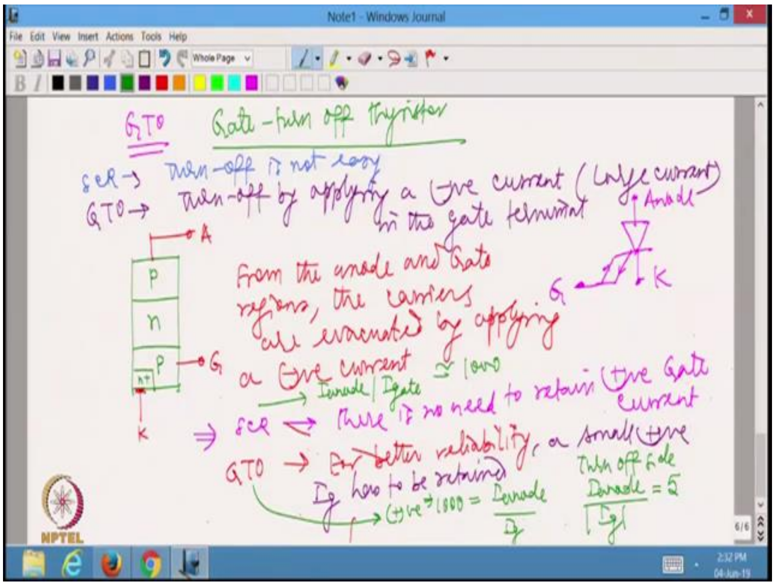
The Triac is a five layer device I told you, so we are going to have something like P,N and P, these are the three layers then I am going to have n+ here and I am going to have one more n+

here. Now my gate may be connected basically from here. This is the gate terminal. Let me call this terminal as MT2 and let me call this terminal as MT1. So these are the three terminals that are available.

And Triac can be fired by having MT1 with respect to MT2 as positive and simultaneously gate is also negative with respect to MT2. Or I can also have MT1 with respect to MT2 as negative, which means MT2 is positive, at that point gate is also positive with respect to MT2. So I can have essentially any of them. So, gate can be positive pulse or negative pulse and it is always measured let us say with respect to MT2 and I am going to have essentially the Triac being fired in either direction.

So we are going to see that normally the Triac is going to be used in, you must have seen fan regulators, electronic fan regulator, so in that Triac is very commonly used. So, if you look at electronic fan regulator what we apply is a single phase voltage like this and we are going to apply the voltage only for a short while like this. So, which means I will fire probably during the positive half cycle at some α and during the negative half cycle at some other α which is $\pi+\alpha$ .So I would see that normally the RMS value of the voltage is going to be controlled by either advancing this or retarding this. So, I will be able to control the RMS value of voltage and hence the speed. It is also used in dimming the lamps either it is at home or stadiums and so on. In those cases, the Triac is very commonly used for AC voltage control.

(Refer Slide Time: 66:04)



So, let me probably conclude the thyristor topic by getting into what is known as GTO. GTO stands for gate turn OFF thyristor. So, what we saw in the case of normal SCR is turn ON is very, very difficult turn OFF is not easy. Whereas in gate turn OFF thyristor we will be able to turn it OFF by applying a negative current, but this negative current will be a large current in the gate terminal.

So, by applying a positive current in the gate terminal, which is a small current we are going to turn ON whereas in GTO we will be able to turn it OFF by applying a large negative gate current. The GTO symbol is somewhat like this. I am going to have essentially this is the normal SCR symbol we see but here the gate is going to have, one is going to show the current inward and the other one is going to show the current outward and this is the gate, this is the anode, and this is the cathode.

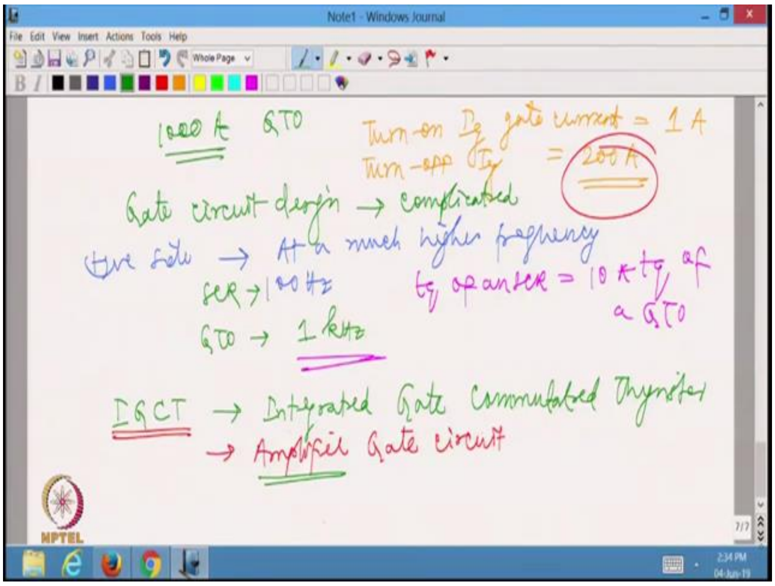
This is how the symbol is normally which indicates that the current can go out or go in to the gate terminal. The GTO actually looks somewhat like this, if I am going to see the basically that this is P N P, I am going to have actually a n which is highly doped and this is going to be actually my cathode and this is going to be my anode and this is going to be the gate. So in this gate I have to make sure that the current can go in either direction.

Normally when the thyristor is conducting, you are going to see that lots of holes are going to be here. Essentially by applying a negative current you are going to evacuate all that hole. So from the anode and gate regions, the carriers, charge carriers are evacuated by applying a negative current. One major problem we face with GTO is that we normally see that even after turn ON in SCR there is no need to retain the positive gate current.

Once you give the gate current, it will just remain ON. After that you do not need to give gate current but in GTO for better reliability if I want to have a better reliability at least a small gate current, a small positive gate current has to be retained. This is one problem whereas one more problem is in SCRs normal you would see if I look at $\frac{I_{anode}}{I_{gate}}$, this is of the order of 1000.

The current amplification is really, really good in the case of SCR whereas in GTO in the positive side I would say I will have a current gain of 1000 approximately which is I anode by Ig. Whereas if I look at the negative side that is the turn OFF side, I am going to have I_{anode} by I_g magnitude. I am talking about magnitude because it is negative current, will be only of the order of 5 or 6 nothing better than that.

(Refer Slide Time: 70:36)

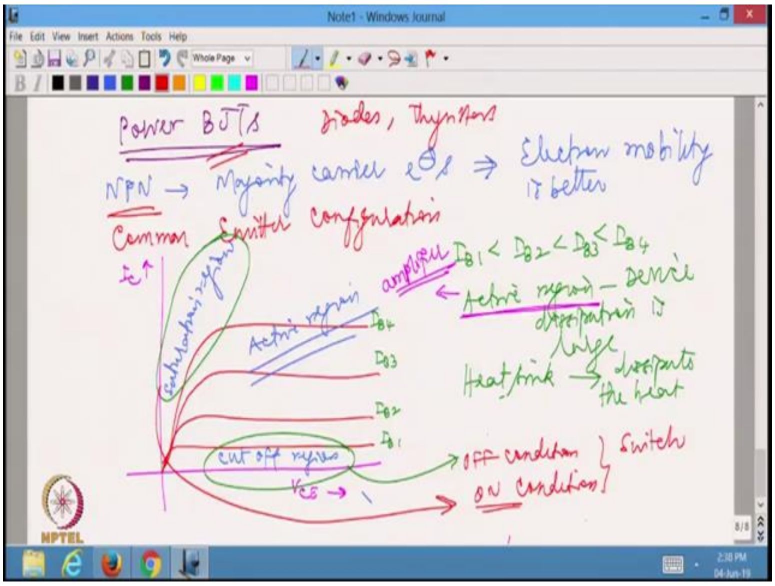


So for example, if it is a 1000 ampere rated GTO, I am going to require turn ON current, gate current, I_g, is going to be only of the order of 1 ampere whereas turn OFF gate current is going to be of the order of almost 200 amperes. So, you can imagine this 200 amperes is way too high, so gate circuit design is going to get very complicated compared to an SCR. But the positive side of it is we would be able to operate at a much higher frequency. So, if I say that normally thyristors work only around 100 Hz that is the normal operating frequency of an SCR.

GTO can easily operate until 1 kHz because normally if I compare the turn OFF time of an SCR, this will be almost 10 times the turn off time of a GTO. So the operating frequency can increase 10 fold, this is the advantage of GTO. But there are some new devices that have been designed by Mitsubishi and GE which is known as integrated gate commutated thyristor which is actually able to have an amplifier in the gate circuit.

There is an amplifier in the gate circuit, this is a built-in amplifier, so you can have a lower current for turn OFF as well and able to work very well. So, this is really becoming popular, this combines the advantages of SCR as well as GTO by including an amplifier in the gate driver.

(Refer Slide Time: 73:01)



Now we are now slowly moving to the transistors, so let us start now with power BJT's. So far whatever we discussed they were all coming under the category of thyristor. Initially we talked about diodes then we talked about thyristor. Now we are coming to this bipolar junction transistor, this is exactly similar to the electronic transistor but only thing is that most of the times we use only NPN not PNP because in this case majority carriers are going to be electrons.

And electron mobility is generally better than whole mobility. And we are looking at very large current, so that is the reason why generally we go for NPN and not for PNP. And normally we look at this in common emitter configuration where I am going to give a base drive and normally you must have known the transistors have three regions of operation. One is going to be cut off, let me just draw how the transistor characteristics are, I_c is plotted with respect to V_{CE}, this are the transistor characteristics are.

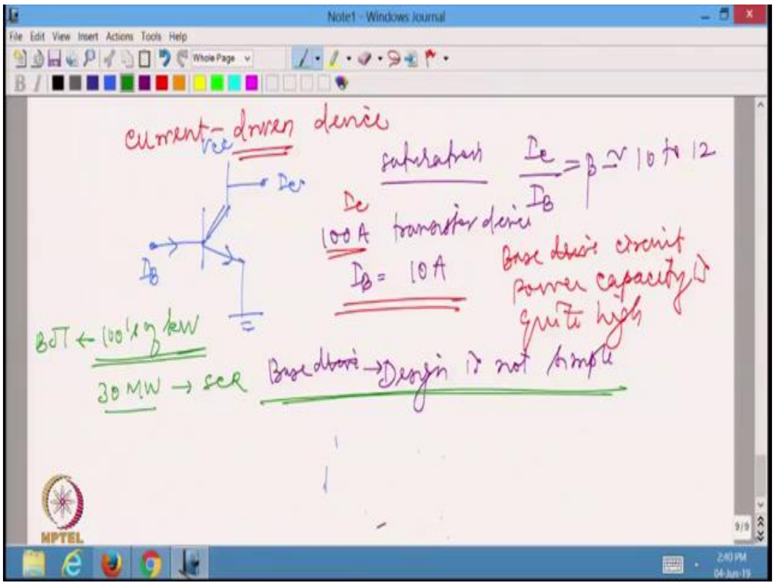
So I will have maybe for a particular gate current this is how it is and another gate current it is going to be like this and another gate current it is going to be like this and so on, this is how it is. So let me call this as may be I_{B1}, this is corresponding to I_{B2}, this is corresponding to I_{B3} and so on. Very clearly the collector current is increasing as the current is moving from I_{B1} to I_{B4}. So I would have I_{B1} as the least I_{B2} then I_{B3} and I_{B4}.

If you look at this there are distinctly three regions of operation, this is the cut-off region, this is the saturation region where V_{CE} is almost a constant and this is going to be the active region wherever I have written here this going to be active region. In active region neither V_{CE} is very small nor I_c is very small, so generally in active region we see that device dissipation is large. If the device dissipation is large, that means I have to have a very large heat sink to actually dissipate that heat.

So it is not a good idea to operate this in the active region. If I want very high heat sink, big heat sink then it is going to increase the weight of the converter also. So normally this active region is only used when the transistor is used as an amplifier which is normally analog electronic circuit application. Whereas in power electronics I am either going to operate in cut-off region or going to operate it in saturation region.

So whenever it is operating in cut-off region, it will be in off condition and whenever it is going to operate in saturation region it will be in on condition. So I am going to operate the transistor only as a switch. So I am essentially turning on and turning off depending upon how much is the gate current that I am giving.

(Refer Slide Time: 66:57)

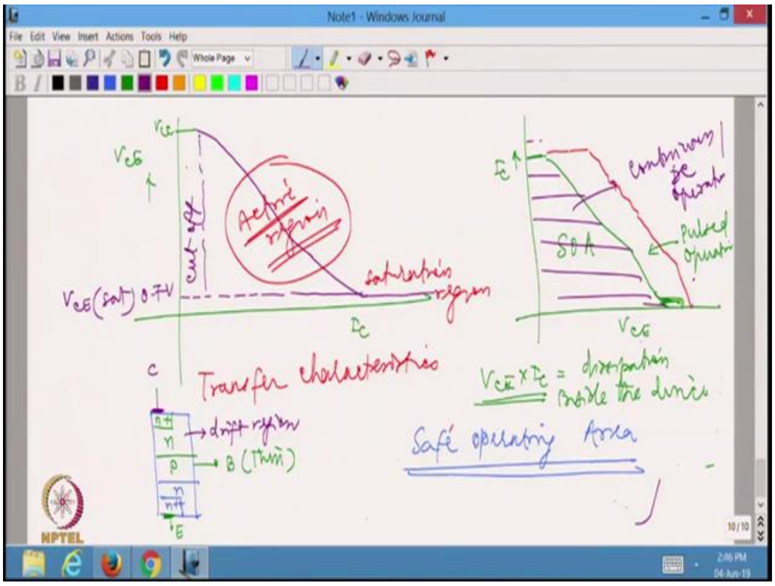


So transistor happens to be a current driven device or current control device. So what I would see is, if this is my NPN transistor symbol I am going to get give a particular value of I_B this is probably grounded and what I am taking from here is I_C. And what I am applying here is V_{CC} through a resistance. If the device is in saturation, I am normally going to get I_C divided by I_B which is beta that will be only anywhere between 10 to 12.

So, if it is 100 ampere transistor device, I will require almost IB equal to 10 ampere. These 100 amperes obviously specifies I_C, so IB has to be 10 ampere because of which the based drive circuit, power capacity is quite high. If this is quite high, I am going to definitely have the design is not simple. This is one of the major problems of this transistor because the base drive design is not simple, not much of research has taken place in the transistor, that is why the ratings are still limited.

You have the transistor rating only of the order of hundreds of kilowatt at the most, nothing more than that. Whereas in thyristor I have already told you that almost 30 megawatt one single SCR can handle whereas hundreds of kilowatt only one particular BJT can handle. It is not really good in terms of the power capacity.

(Refer Slide Time: 79:05)



And if I actually look at normal transfer characteristics of the transistor, I am going to have V_{CE} on one side and I_C on the other side. So, I am normally going to see that V_{CE} is actually equal to V_{CC} itself when the device is in cut-off region. So this is the cut-off region. Whereas I am going to see that I am going to have slowly the reduction in V_{CC} and it is going to come to a minimum value, so this actually is going to be corresponding to V_{CE} equal to 0.7 volts approximately which is actually V_{CE} saturation.

And this is essentially the saturation region of the transistor, obviously whatever is in the middle is the active region. This is generally known as the transfer characteristics of the transistor BJT. So under this condition we can very clearly say that the active region is hardly ever traversed by any of the power BJT's. Either I am going from off condition to on condition which is saturation condition or from saturation condition to off condition, only during that time this active region is going to be traversed. Otherwise never do we operate in active region as far as my BJT is concerned.

But if I try to look at the normal operation of the transistor I can say probably this is I_C and this is V_{CE}, I am probably going to have for a rated I_C. I am probably going to have very very small V_{CE}. So V_{CE} times I_C is going to be the dissipation inside the device because please note V_{CE}

is the voltage across the device between collector and emitter and I_C is the current carried by the device. So, the product of these two is the dissipation inside the device.

As our I_C decreases V_{CE} will increase, so I may have something like this and then again I am going to have probably some portion where I am going to have V_{CE} to be very small but I_C to be very large. So, I would call this as the safe operating area. Safe operating area for the transistor which means within this region I am going to have the heat dissipated, whatever is the heat dissipated within the device it can be easily shunted out. But if I try to actually load it more than this current or go for a higher voltage, I am going to have a good big problem. So, this is for continuous or DC operation.

But if I am going to have it in pulsed operation. For some time I am going to turn it on and some time I am going to turn it off then probably I can increase the limit slightly. So this is essentially corresponding to pulsed operation. So if I am going to have some pulses only then I would be able to dissipate more heat because every now and then my device gets some rest. So in general whenever we design a transistor circuit we have to check whether it is within safe operating area of the device or not. That is what is going to actually tell us whether I will be able to operate it safely.

So far we have seen at least the transistor structure. so I should say generally in transistor structure what happens is, I am going to have n substrate inside which I am going to have n plus doping quite a lot of doping. So this will correspond to the emitter. Then I am going to have the p which will be corresponding to the base..

So this is essentially my based terminal which is very thin, normally this is going to be thin. Then after that I am going to have one more n inside which I am going to have again n plus that is heavy doping. So this particular portion is going to correspond to the collector, normally we call this region as the drift region. This drift region is going to offer some amount of resistance, the longer the drift region the resistance will be somewhat larger.

So we had seen so far basic structure of the transistor, we have seen the transfer characteristics, we have seen why the base drive requirement is somewhat higher and what are the three regions of operation. We had also looked at what is the safe operating area of the device. In the next class we will be looking at the series and parallel operation, we will also be looking at the protection for the BJT, Power BJT.