Advance Power Electronics and Control
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Lecture - 04
Device Physics II

Welcome to our second lecture on device physics and the fourth lecture of advance power electronics and control. We shall continue with our discussion which was left you know previous discussions that was thyristor.

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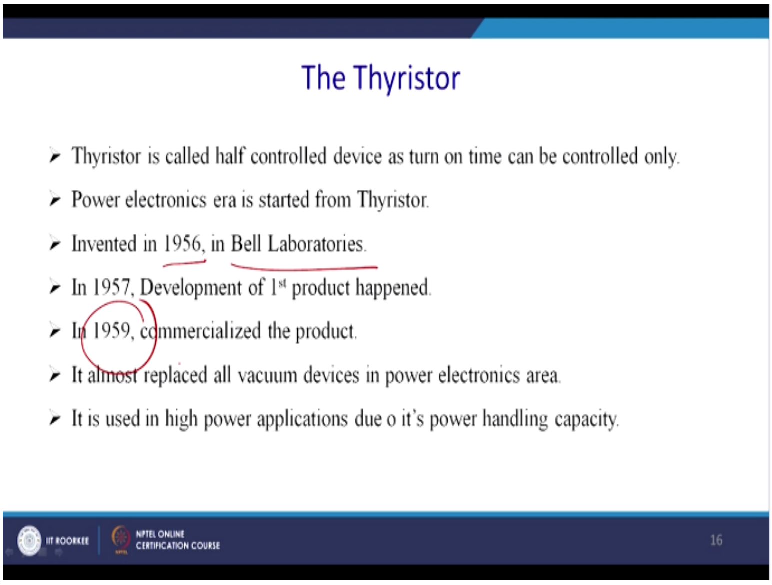

The Thyristor

- Thyristor is called half controlled device as turn on time can be controlled only.
- Power electronics era is started from Thyristor.
- Invented in 1956, in Bell Laboratories.
- In 1957, Development of 1^{st} product happened.
- In 1959, commercialized the product.
- It almost replaced all vacuum devices in power electronics area.
- It is used in high power applications due o it's power handling capacity.

So we have told that actually we have commercialized, this product is commercialized in 1960 and it has replaced thermionic-based emission switches like vacuum tubes and all and it is used for the high power handling capabilities and true power electronics starts with the inventions and application of the thyristors.

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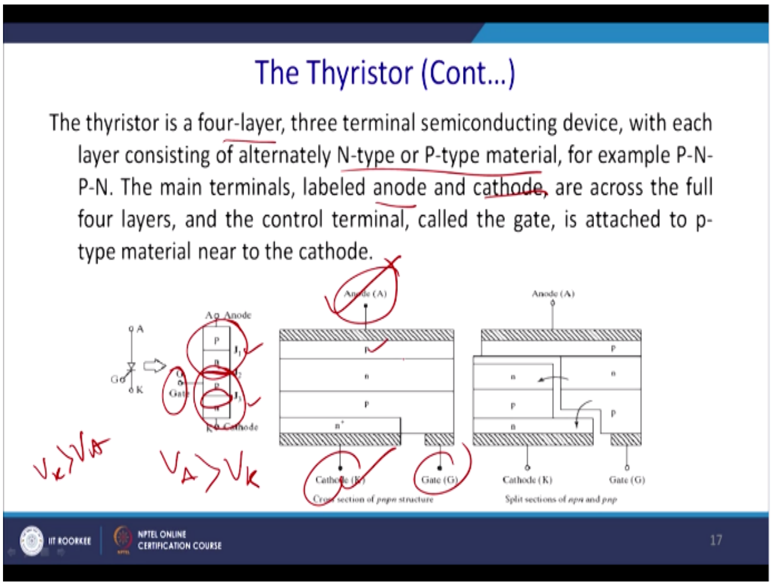

The Thyristor (Cont...)

The thyristor is a four-layer, three terminal semiconducting device, with each layer consisting of alternately N-type or P-type material, for example P-N-P-N. The main terminals, labeled anode and cathode, are across the full four layers, and the control terminal, called the gate, is attached to p-type material near to the cathode.

Cross section of *pnpn* structure

Split sections of *npn* and *pnp*

So what essentially thyristor is, thyristor is essentially we can think of that one PN junction diode, another PN junction diode is connected in series. So essentially what happened, since when you applied a voltage actually it is a VA is>VK or cathode. Then, these junctions you know this J2 is automatically going to be reverse biased and this junction J1 and J3 is forward biased and that gives features of forward blocking capability, so this device is normally off.

Why? If you apply a voltage VA>VK junction J2 is reverse biased; only leakage current will flow. Similarly, if VK is>VA then naturally J3 and J1 are reverse biased and then also it will be blocked but you can make it on with the external devices or external way. So forth this is and you know you got a gate, you can inject external current that will basically break down the junctional barrier object and it comes into the forward conduction mode.

Please mind it, never give a great trigger while VK is>VA, it may damage the thyristor. So let us come into the discussions. The thyristor is a four-layer, you have a four-layer you can name it p1 n1 p2 n2 like that. Three terminal devices you got anode, you got cathode and you got gate which each layer consisting of alternatively PN type material. For example, PN, PN the main terminals are labeled as anode and cathode across the full four layers.

And the control terminal is called gate and it is attached to the p-type terminal near to the cathode. So this is the configuration of it and you know what happen if you actually truncate the thyristors, then you can see two transistors, so it is said to be a two transistors model PNP and NPN and in between they have got connections. So generally thyristor is analyzed by the two transistors model for its turn-on applications.

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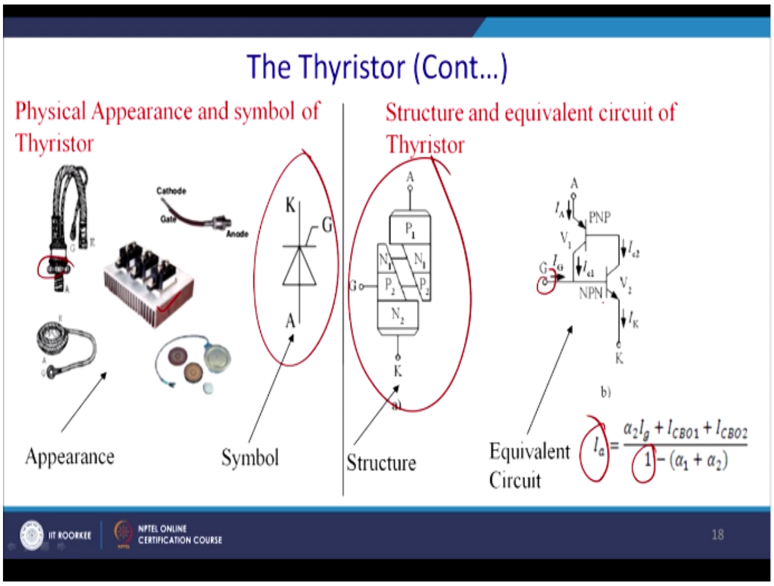

The Thyristor (Cont...)

Physical Appearance and symbol of Thyristor

Structure and equivalent circuit of Thyristor

Appearance

Symbol

Structure

Equivalent Circuit

$$I_a = \frac{\alpha_2 I_g + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)}$$

So different kind of thyristors appearance, this is the symbol of the thyristors. This anode, cathode and gate and you will have a different kind of pictures which is basically the heat sink, it required to put onto the heat sink. This is anode and ultimately it will be go into the heat sink and will can tighten the screws and there is a different kind of segments and current handling capabilities of the thyristors in fax devices, it can go as high as kilo ampere rating.

So power handling capabilities of these devices can go as high as you know megawatt level. So this is the actually a truncated version of the thyristors. So we can visualize as two transistors model, one is PNP; another is NPN where actually Ig is injected. Thus, you know if you write the KCL from this point to this point, ultimately Ia becomes alpha Ig+ICB1, this is basically the base current of transistor 1 and ICB2 is a base current of transistor 2.

And you will find that 1-alpha 1+alpha 2. Here this alpha 1 and alpha 2 are essentially are not constant, this value can change depending on the value of injections of this value and generally this value is alpha 2 generally changes and it may so happen that by changing this value, this denominator can be made close to zero and thus high current will flow and we say that thyristor is triggered or latched.

And it will continue to flow till some external action has been added to actually put it off or commutation. Commutation itself is a big chapter of discussions but with the invention of the GTOs and all those things there is literally phasing out. So let us come to the different layers and its concentrations. So it is called p-emitter region.

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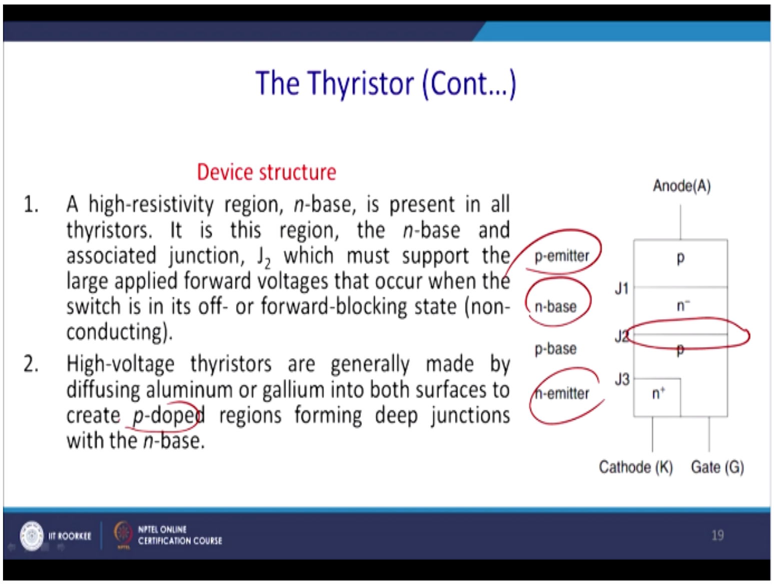

The Thyristor (Cont...)

Device structure

1. A high-resistivity region, *n*-base, is present in all thyristors. It is this region, the *n*-base and associated junction, J_2 which must support the large applied forward voltages that occur when the switch is in its off- or forward-blocking state (non-conducting).
2. High-voltage thyristors are generally made by diffusing aluminum or gallium into both surfaces to create *p*-doped regions forming deep junctions with the *n*-base.

This is called n-base region (()) (07:09) it is called p-base region and it is n-emitter region. So this is the model and a highly resistive region n-base region is present in all thyristor to give a blocking capability and it is the region n-base and associated junction J2 which must support the large applied forward voltage that occurs when switch is off or the forward blocking state or the non-conducting state, so this is the region.

High voltage thyristors generally made by diffusing aluminium or gallium into both the surface to create p-doped region forming a deep junction in the n-base. So that will reduce the all-state conduction loss.

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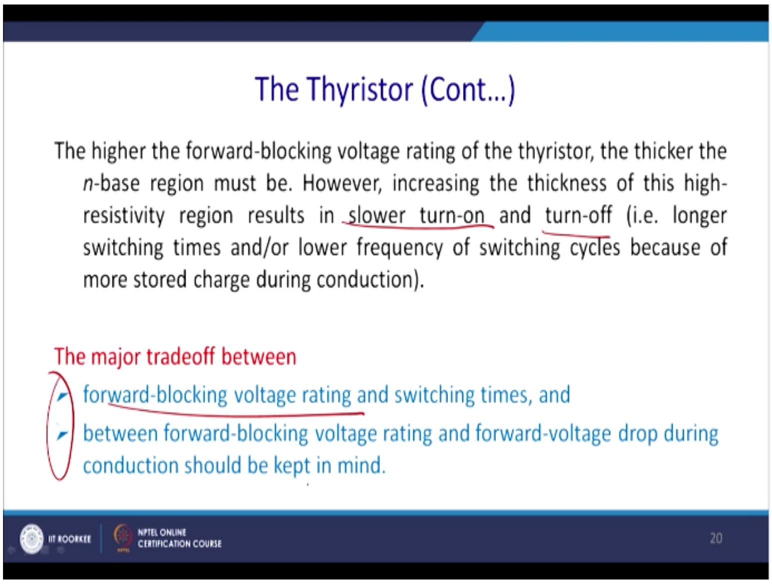

The Thyristor (Cont...)

The higher the forward-blocking voltage rating of the thyristor, the thicker the *n*-base region must be. However, increasing the thickness of this high-resistivity region results in slower turn-on and turn-off (i.e. longer switching times and/or lower frequency of switching cycles because of more stored charge during conduction).

The major tradeoff between

- forward-blocking voltage rating and switching times, and
- between forward-blocking voltage rating and forward-voltage drop during conduction should be kept in mind.

The higher forward blocking voltage of the thyristors, the thicker n-base region, it is basically used; however, increasing the thickness of this resistive region will actually will reduce the operations, reduce the faster operation that means it will slower the turn-on and the turn-off. So it will take larger time to turn it on and require higher gate current and also you know you have to do the commutation put it off when actually we may have a natural commutation.

In case of the rectifier operation, when you applied to the AC sources, you get a negative voltage applied cathode to anode. So thus turn off also will be slower and it will be suitable for the low frequency switching devices because most of the trap charge required to be removed and that takes lot of time than the faster devices. So there are something we require to trade it off, we have to put according to the applications.

So if the thyristors has a high blocking forward voltage generally it is very slower device and switching time will be actually slow. Between forward blocking voltage rating and the forward voltage drop during conduction should be kept in mind. Since high voltage thyristor generally of the aluminum and the gallium drop surface, so that gives a higher voltage blocking capability.

But it also increases the all-state conduction losses or the resistance of the devices. So we have to trade it off. For this reason, we required to choose suitable devices. We should not choose a high blocking thyristors where we will find pretty high conduction losses and reverse you choose devices with a low conduction losses but it cannot sustain that forward blocking capability or the reverse blocking capability.

Then, circuit will burn simply. So for this reason, designer has to judicially use these features of the thyristor.

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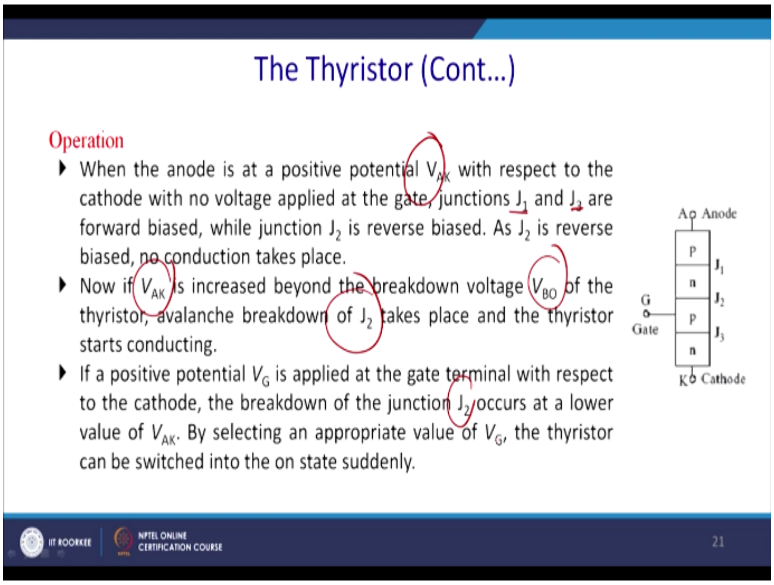

The Thyristor (Cont...)

Operation

- When the anode is at a positive potential V_{AK} with respect to the cathode with no voltage applied at the gate, junctions J_1 and J_3 are forward biased, while junction J_2 is reverse biased. As J_2 is reverse biased, no conduction takes place.
- Now if V_{AK} is increased beyond the breakdown voltage V_{BO} of the thyristor, avalanche breakdown of J_2 takes place and the thyristor starts conducting.
- If a positive potential V_G is applied at the gate terminal with respect to the cathode, the breakdown of the junction J_2 occurs at a lower value of V_{AK}. By selecting an appropriate value of V_G, the thyristor can be switched into the on state suddenly.

Operation, when anode is positive potential that in VAK is positive with respect to the cathode and no voltage is applied to the gate, it is said to be the forward blocking mode. The junction J1 and J3 are the forward biased while junction J2 are reverse biased and J2 will actually block the whole voltage. If VAK is increased beyond the breakdown voltage of BO that has been prescribed in the data sheets for the thyristors, Avalanche breakdown of J2 takes place and thyristor start conducting.

But sometime it may damage the thyristors because you know when actually it start conducting, current is also high and it has got a considerable voltage drop across the junction and that if you properly heat is not dissipated this mode may damage the thyristor. If applied a potential VG at the gate terminal with respect to the cathode, the breakdown of junctional voltage J2 occurs at considerably lower voltage.

It can be as less than 10 times less or 20 times less depending on the amount of the current you are injecting. By selecting the appropriate value of the VG, the thyristor can be switched on on a sudden state.

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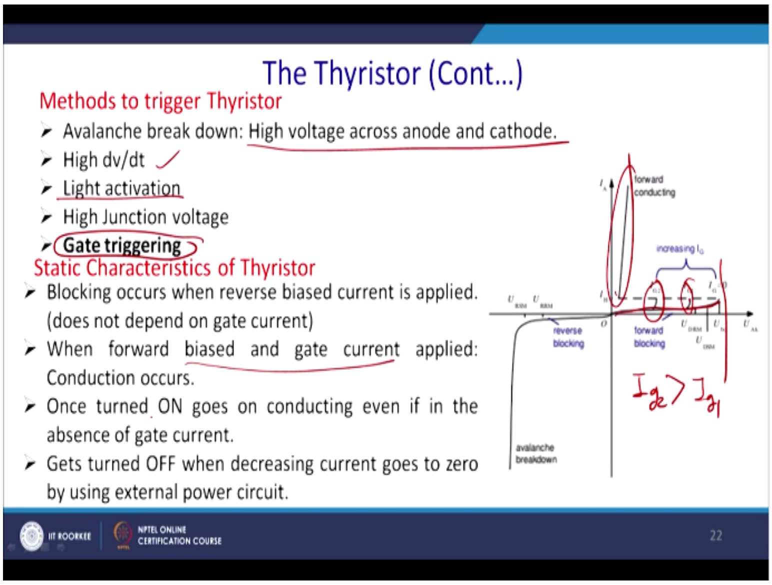

The Thyristor (Cont...)

Methods to trigger Thyristor

- Avalanche break down: High voltage across anode and cathode.
- High dv/dt ✓
- Light activation
- High Junction voltage
- Gate triggering

Static Characteristics of Thyristor

- Blocking occurs when reverse biased current is applied. (does not depend on gate current)
- When forward biased and gate current applied: Conduction occurs.
- Once turned ON goes on conducting even if in the absence of gate current.
- Gets turned OFF when decreasing current goes to zero by using external power circuit.

So this is the I-V characteristics of the thyristors, once VG is zero, so this zone is called the forward blocking region and the current leakage current will flow through it and thereafter what happen forward leakage current will flow through it and thereafter when it will cross the value of VBO, it will be triggered and current will flow from this. If you keep this value of IG of some value let say here around half of the VBO or two third of the VBO, it can actually come this point to this point.

And it will give you a drop of very small drop. Similarly, you can turn it on from the VBO, again you please remember that IG2 should be much greater than IG1. So larger the gate current, you get lower the forward blocking voltage. So apart from the gate triggering, there is a different method of gate triggering, Avalanche breakdown that is actually high voltage applied across the anode and cathode.

Dv/dt gate triggering if you apply high rate of change of voltage that also leads to the triggering, for this reason it is not advisable to use thyristors in pulse kind of waveform. If you have a square pulses which has a very high dv/dt which may falsely trigger the thyristors. So for this reason, will not use it most of the cases and light activation thyristor there is a special kind of thyristors when the depletion region can be actually reduced by activation of the light or doping charges.

And high junction voltage and what we generally use is that gate triggering. Gate triggering is something we use for the triggering thyristor that is a common mode of practice. A different kind of gate triggering can be there that is RC or we can have a UJT based gate triggering that different kind of gate triggering circuit may be used.

So characteristics of the thyristors let us come to it. So blocking occurs when reverse biased current is applied depending on the gate current. When forward biased and the gate current is applied, conduction takes place and it will be high current and actively it will be blocked by the load of the system. Once turn on goes on, gate is no longer required. You can put up the gate, so it will just require to turn it on.

Once it is turn on, gate circuit may be put off and thus you can avoid a constrained dissipation of the current across the gate. Gate turn off when decreasing current goes to zero because of the external power circuit also.

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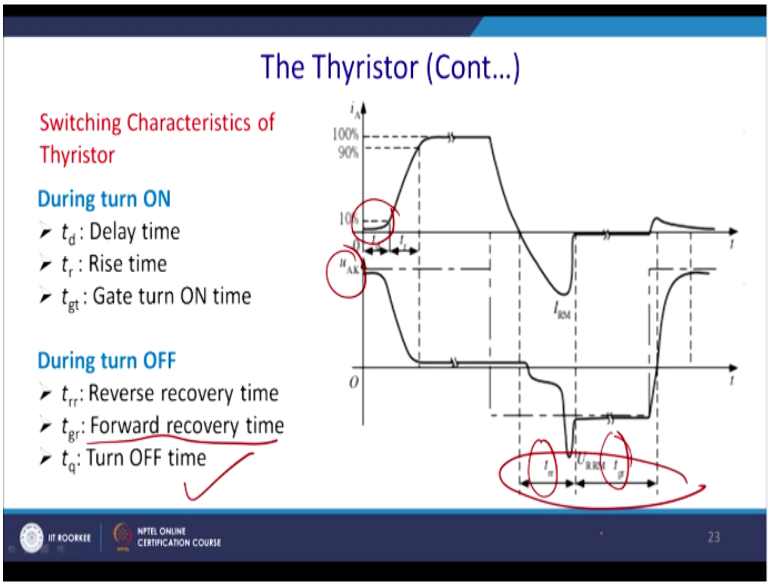

The Thyristor (Cont...)

Switching Characteristics of Thyristor

During turn ON
- t_d : Delay time
- t_r : Rise time
- t_{gt} : Gate turn ON time

During turn OFF
- t_{rr}: Reverse recovery time
- t_{gr}: Forward recovery time
- t_q: Turn OFF time

Now this is actually the switching characteristics of the thyristors. So this is actually the voltage across VAK that is anode to cathode voltage and it will drop. You can find that current through the thyristor will take around 10% time to actually to its peak value, it would whatever time it will take 0% to 10% or the leakage current you can assume to be 0% to 10% of the load current or the final rated current, so that current is said to be td or the delay time.

Thereafter, you will have 10% to 90% we say that is a rise time, so faster is the rise time so faster that will be a faster device. If rise time is slower, it will be slower device. Thereafter, it takes you know some amount of time to actually settle down and tgt is a gate turn on time.

Similarly, we come to the reverse recovery time, reverse recovery time totally depends on the current.

Reverse recovery time is the total current actually trr and this one is actually tgr and total time is said to be the turn off time that is represented by the tq. Again, actually like that we require it is a very important feature of the reverse recovery time. So for this reason, you know when it will be off, when both are recover, the recovery time means actually it has got a forward blocking capability.

But if you have a false triggering gate it will turn conduction. For this reason, we got a forward recovery time or this total actually combines and then we can say that thyristor has hold the forward blocking capability. So you have to wait till time trr+tgr.

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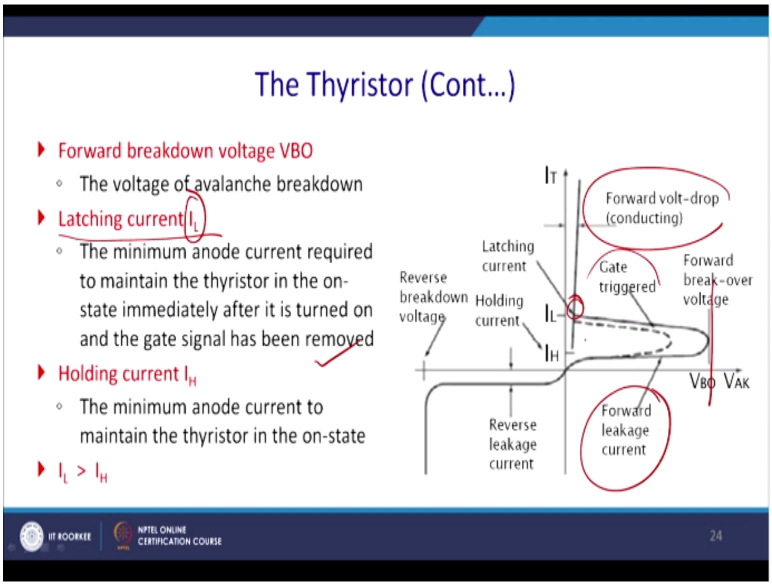

The Thyristor (Cont...)

- Forward breakdown voltage VBO
  - The voltage of avalanche breakdown
- Latching current I_L
  - The minimum anode current required to maintain the thyristor in the on-state immediately after it is turned on and the gate signal has been removed
- Holding current I_H
  - The minimum anode current to maintain the thyristor in the on-state
- $I_L > I_H$

So there are few important terms that is forward breakdown voltage VBO that is this has been prescribed by your data sheet, it is done by the destructive test of the devices generally it does not survive after the test. So we generally will do with the few samples and presented in the data. So this is VBO and that is called forward breakdown voltage and once it was actually in a forward mode, forward blocking mode some amount of current will flow that is called forward leakage current.

That is around 10 to the power 4 times lower than this actually the thyristor current and thereafter you have a gate triggered. So accordingly voltage will change and this is a forward conduction drop. Generally, it slants almost it, due to this ohmic losses, it will be little bit slanted, so if it is because you know as there is two diode in series. This model is essentially can we think of that two diode put into the series.

And since the silicon based diode of course you can assume that both will have a junction and drop of J1 and J3 in forward conduction mode of 0.7 and 0.7 that gives you the 1.4 volt but depletion region is made in a such a way by dropping of the aluminium and other things but forward conduction mode will try to restricts less than 1.4 volt. That is actually one of the technical advancement has been achieved in case of the thyristor.

There are two important parameter, one is called latching current. Latching current is associated with the turn-on process. Once thyristors is put on, thyristor current required to go more than the value of IL. Then, if you remove the gate, then also it will be in a forward conducting mode. So thus the minimum anode current is required to maintain the thyristor in on state, immediately after its turn on and gate signal has been removed.

Same way holding current, what is holding current? This current should minimum current it should hold to keep it in a conduction mode. So that is called a holding current and that is associated with the turn on of the thyristors. If the current is above, the holding current, thyristors will stay in a forward conduction mode. The minimum anode current maintain the thyristor in an off state.

And of course from this figure it is quite clear that this holding current should be less than the latching current.

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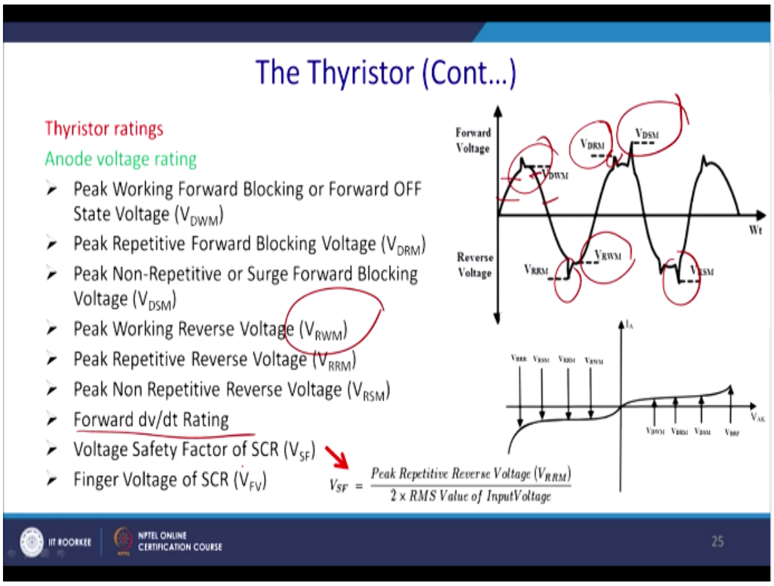

The Thyristor (Cont...)

Thyristor ratings

Anode voltage rating

- Peak Working Forward Blocking or Forward OFF State Voltage (V_{DWM})
- Peak Repetitive Forward Blocking Voltage (V_{DRM})
- Peak Non-Repetitive or Surge Forward Blocking Voltage (V_{DSM})
- Peak Working Reverse Voltage (V_{RWM})
- Peak Repetitive Reverse Voltage (V_{RRM})
- Peak Non Repetitive Reverse Voltage (V_{RSM})
- Forward dv/dt Rating
- Voltage Safety Factor of SCR (V_{SF})
- Finger Voltage of SCR (V_{FV})

$$V_{SF} = \frac{\text{Peak Repetitive Reverse Voltage } (V_{RRM})}{2 \times \text{RMS Value of InputVoltage}}$$

Now these are the few parameters you know it is quite important while analysis the thyristors and use it the thyristors. First of all, peak working forward blocking voltage or forward off state voltage VDM. So this is basically the VDM which is quite important because since the repetitive supply is there, so this voltage has to be block, you may trigger this point, you may trigger this point, you may trigger this point, you may trigger this point.

So safely it should be able to block the value of the medium then value will be prescribed. So peak repetitive forward blocking voltage, this is VRM because sometimes we may have a notch and notch actually follows so that value will be actually pretty peak repetitive forward blocking voltage. Peak non-repetitive or the surge blocking voltage if all of a sudden high voltage comes that is said to be the surge and it has not has (()) (21:20). Then, that voltage is said to be the actually VDSM and the VDSM value also will be prescribed.

Some notches may come, maybe after one hour or two hours or even after a day. So that value actually said to be the VDSM. Peak working reverse voltage, it is same so as this actually forward voltage, this is basically VRWM this one. Then, peak repetitive reverse voltage, this one it is same as this one but it is in a reverse direction. Peak non-repetitive surge, so this will be this one and this has to be actually almost reciprocal to the forward voltage and we required to understand that forward dv/dt rating.

So this is quite important, you know that supply voltage undergoes some changes if it is say sinusoidal wave it is quite slow. If it is a pulse kind of voltages, then it will have a very fast dv/dt. So dv/dt rating of this device required to be prescribed, otherwise we require to put a dv/dt protection circuits that is called snubber. We shall take out the circuit protections in totality. Thereafter, voltage safety factors that is VSF that is given by peak repetitive reverse voltage by 2*RMS value of the voltage.

So some value will come out accordingly life of the device will be decided. So more the safety factor more will be the life of the device but definitely cost of the component will go high and finger voltage of SCR that is called FV. So these are the few parameters has been prescribed in your data sheets and we will continue to actually have operating on those data sheet for the practical design aspects.

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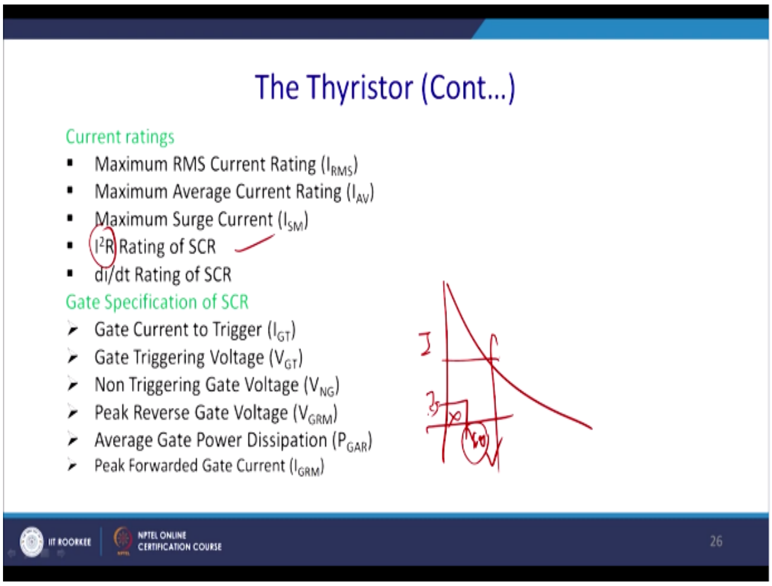

The Thyristor (Cont...)

Current ratings

- Maximum RMS Current Rating (I_{RMS})
- Maximum Average Current Rating (I_{AV})
- Maximum Surge Current (I_{SM})
- I^2R Rating of SCR
- di/dt Rating of SCR

Gate Specification of SCR

- Gate Current to Trigger (I_{GT})
- Gate Triggering Voltage (V_{GT})
- Non Triggering Gate Voltage (V_{NG})
- Peak Reverse Gate Voltage (V_{GRM})
- Average Gate Power Dissipation (P_{GAR})
- Peak Forwarded Gate Current (I_{GRM})

Apart from that, we have current ratings, that is same that is maximum RMS current rating and thereafter maximum average current rating, mostly it will be for the DC value, maximum surge current rating, all of a sudden if high current comes it has to sustain and thyristors I square R rating. So for the conduction losses was the one it is on state and thereafter di/dt rating, so if it undergoes very high di/dt, then also it can damage the thyristors.

For this reason, we required to put a di/dt protecting circuit and that we will discuss about the di/dt and dv/dt protections but thyristor has to ensure that we will have its di/dt rating; we are operating in a separate sheet. Thereafter, we have some specification on the gate current. So gate current to trigger there will be a minimum current there is a safety operation where it is not triggered because noise also gives you some amount of the gate current.

But that should not trigger the thyristor falsely, so for this reason, gate current to trigger that value will be there. Similarly, we will have some value will be there actually, we shall come into the discussions. So gate voltage to trigger, there will be some voltage. So this VG and this IG, this is the minimum value. This zone will not trigger; this may come due to the noise. So non-triggering gate voltage, this is basically non-triggering gate voltage.

And peak reverse gate voltage, the maximum voltage you should apply. You should not go beyond that; we may damage the gate. Peak reverse gate voltage, again that comes into the picture in a reverse mode. So you should not allow actually the reverse gate voltage. Average gate power dissipation, this is the power line so you have to fix into it in the power line. You should not go beyond the power dissipation.

Otherwise, the gate circuit will fail and peak forward gate current that value also will be specified by the thyristors.

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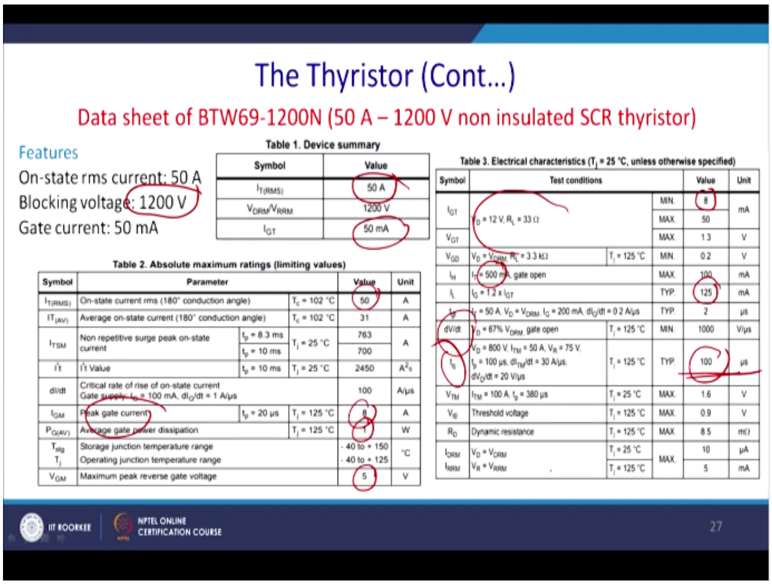

The Thyristor (Cont...)

Data sheet of BTW69-1200N (50 A – 1200 V non insulated SCR thyristor)

Features

On-state rms current: 50 A

Blocking voltage: 1200 V

Gate current: 50 mA

Table 1. Device summary

Symbol	Value
$I_{T(RMS)}$	50 A
V_{DRM}/V_{RRM}	1200 V
I_{GT}	50 mA

Table 2. Absolute maximum ratings (limiting values)

Symbol	Parameter			Value	Unit
$I_{T(RMS)}$	On-state current rms (180° conduction angle)		T_c = 102 °C	50	A
$IT_{(AV)}$	Average on-state current (180° conduction angle)		T_c = 102 °C	31	A
I_{TSM}	Non repetitive surge peak on-state current	t_p = 8.3 ms	T_j = 25 °C	763	A
		t_p = 10 ms		700	
I^2t	I^2t Value	t_p = 10 ms	T_j = 25 °C	2450	A^2s
dI/dt	Critical rate of rise of on-state current Gate supply: I_G = 100 mA, dI_G/dt = 1 A/µs			100	A/µs
I_{GM}	Peak gate current	t_p = 20 µs	T_j = 125 °C	8	A
$P_{G(AV)}$	Average gate power dissipation		T_j = 125 °C	1	W
T_{stg} T_j	Storage junction temperature range Operating junction temperature range			- 40 to + 150 - 40 to + 125	°C
V_{GM}	Maximum peak reverse gate voltage			5	V

Table 3. Electrical characteristics (T_j = 25 °C, unless otherwise specified)

Symbol	Test conditions			Value	Unit
I_{GT}	V_D = 12 V, R_L = 33 Ω		MIN.	8	mA
			MAX.	50	
V_{GT}			MAX.	1.3	V
V_{GD}	V_D = V_{DRM}, R_L = 3.3 kΩ	T_j = 125 °C	MIN.	0.2	V
I_H	I_T = 500 mA, gate open		MAX.	100	mA
I_L	I_G = 1.2 x I_{GT}		TYP.	125	mA
t_{gt}	I_T = 50 A, V_D = V_{DRM}, I_G = 200 mA, dI_G/dt = 0.2 A/µs		TYP.	2	µs
dV/dt	V_D = 67% V_{DRM}, gate open	T_j = 125 °C	MIN.	1000	V/µs
t_q	V_D = 800 V, I_{TM} = 50 A, V_R = 75 V, t_p = 100 µs, dI_{TM}/dt = 30 A/µs, dV_D/dt = 20 V/µs	T_j = 125 °C	TYP.	100	µs
V_{TM}	I_{TM} = 100 A, t_p = 380 µs	T_j = 25 °C	MAX.	1.6	V
V_{t0}	Threshold voltage	T_j = 125 °C	MAX.	0.9	V
R_D	Dynamic resistance	T_j = 125 °C	MAX.	8.5	mΩ
I_{DRM} I_{RRM}	V_D = V_{DRM} V_R = V_{RRM}	T_j = 25 °C	MAX.	10	µA
		T_j = 125 °C		5	mA

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So this is the data sheets of the thyristors. You see that you know there are some values. It has a forward blocking capability of 1200 volt and it can carry as high, we are discussing a diode of 3 ampere or 8 ampere and it has a power handling capability of the 50 ampere but you see this ratio, this gate current is 1000 times less, so this is the efficiency counts, the IGT is actually 50 milliampere.

And all the values is provided what has been discussed into the data sheets. So in a different temperature level in a conduction temperature 50 amperes. If it is temperature rises to 100 degree centigrade, it has to be considerably d-rated, it has to be operated to the 31 ampere and all the data has been prescribed. So peak gate current can be 8 ampere, peak power dissipation should be 1 watt.

And maximum peak reverse voltage is 5 volt. Similarly, you will see that actually what should be the IGT, IGT should be it actually prescribed that is 50 milliampere but you can operate anywhere in between actually 8 to 50 so that you can turn it on a different voltages. Similarly, holding current has been prescribed when gate is open. It is 500 milliampere. Similarly, latching current has been prescribed, that should be actually 1.2 times of the IGT.

So from there you can calculate and this value is generally it is actually 1 to 5 milliampere and value of this dv/dt also is given that is actually 1000 volt per microsecond. Similarly, value of the tq that is the turn off time, you can see that, that is in the range of the 100 microsecond. Please recall that you know it is quite slow, in diode we have come out, we have seen a fast diode having a turn off time in nanoseconds.

And snappy diode will have around 2 or 1.2 microsecond but this will take a considerable high amount of time to turn it off. So turn it off of this devices it is quite slower because of the trap charges in junction J2 okay. We shall continue to our discussions. These are the ratings you can follow. So these are the threshold voltages and IDRM and RDRM. So all those data has been actually explained so that student can take out for the design purpose and how to read the data sheet properly.

We shall continue till few aspects of the thyristors in our next classes and followed by some modern devices like IGBT and IGCT. Thank you so much for your attention.