Switched Mode Power Conversion
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Lecture - 3
Controlled Switches

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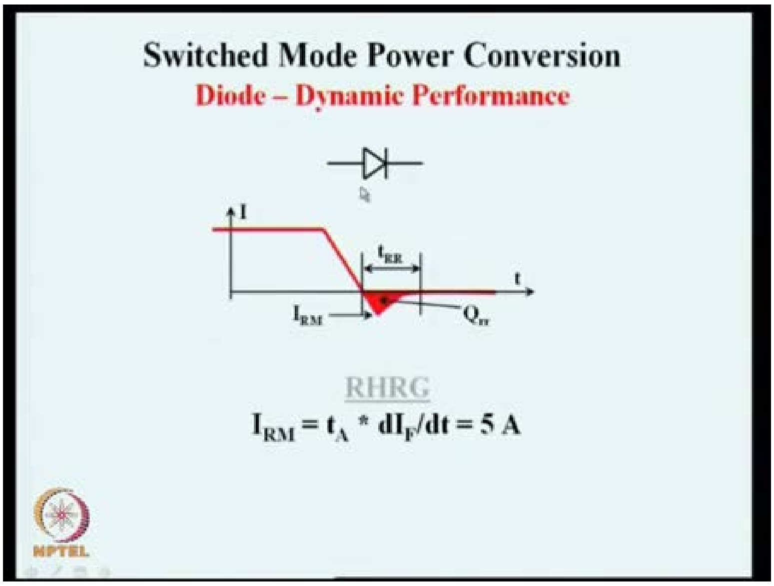

I have to come back to the same topic; we are on the idea of dynamic performance of diodes. We had earlier seen the study state performance of diode as a switch, those where the on state performance voltage drop, off state performance leakage current and so on power losses associated with and so on. Now, we are looking at the dynamic performance, the dynamic performance relates to the switching performance. What happens during the transients, when a diode from a conducting state moves to a blocking state. Unlike other switches, the electronic switches have a different mechanism, in the process of moving from an on state to an off state. The blocking in most of these semi conductor junctions are taking place, because of charge concentrations.

So, whenever a diode moves from an on state to an off state, there is a redistribution of charge in the junction, that is what you see here, you see here as Q r r this is called the reverse recovery charge. And this charge is accumulated in the junction, over a period of time which is given us t R R are the reverse recovery time. And during this time, the device for a short duration conducts in the opposite direction. In the direction which is against the arrow mark in the diode and this is a non ideality in the diode, an ideal diode will switch off and remain in the off state, no current will ever in the opposite direction, but in a real device there is a small duration, when the current flows in the opposite direction charges recover and a fresh balance is established, which carries out the new state, which is the off state. This was the on state and off state (( )) intermediate transient during this transient time, which is the reverse recovery time the device is still conducting partially. And so when you try to use these diodes at very high frequencies, it is necessary to make sure that this high frequency is manageable, through this reverse recovery time as well.

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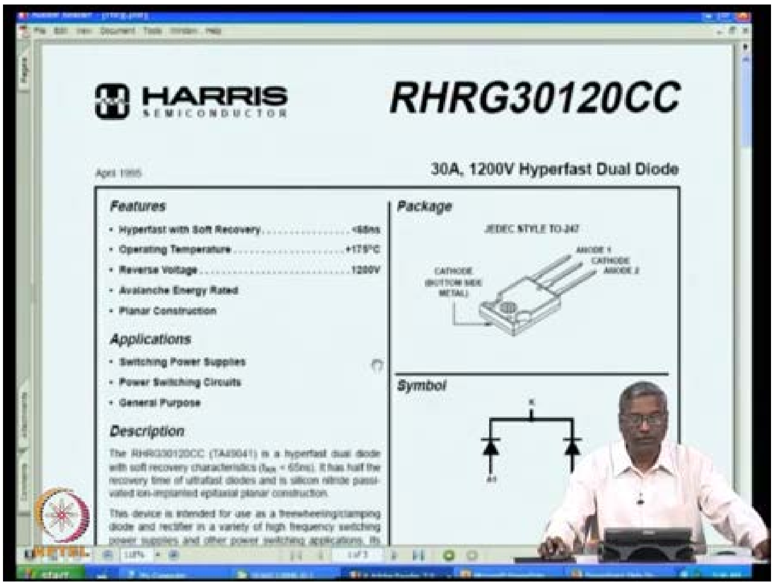

So, what we see here is the data sheet of a particular hyper fast dual diode, these are packed two diodes in one package with k, which is the midpoint and two anodes. Anode 1, anode 2 you can connect them together and use it as a single diode or you can connect it as a center tap rectification application and so on. The metal here is the same as the cathode the middle tag and you will have two anodes in this particular device.

And you can see a single lines specification of the device, which is the 30 amperes, 1200 volts hyper fast dual diode. This is capable of carrying 30 amperes blocking 1200 volts and it is the fast diode, fast diodes have the additional recovery time specified which is 65 nano seconds in this case. Operating temperature is limited to 175 degrees and the reverse voltage, these devices is 1200 volts in the applications are specified.

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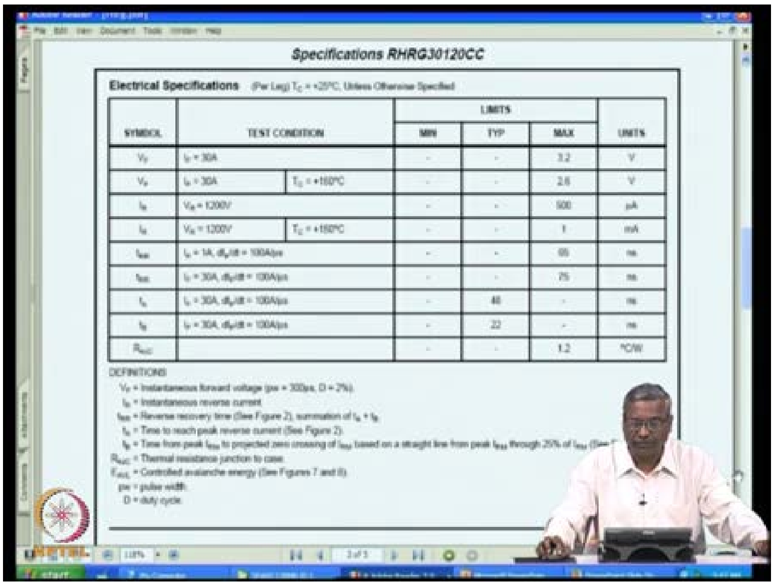

The process of recovery is something which is of interest to us, and you can see here the reverse recovery time is specified as 65 nano seconds maximum. And this is when it is recovering from 1 ampere, when it is recovering from 30 amperes it is 75 nano seconds. So, you see that these reverse recovery time is not really a function of current, it is almost constant, it is nearly 70 nano seconds. Whether, you are recovering from 1 ampere forward current, or you are recovering from 30 ampere forward current.

So, going through a data sheet will be always advantages, it will tell us many of these functional dependencies. You can see very clearly that the diode recovery is independent almost independent of the current from which is recovering, and it is necessary to have a defined rate of change of current during the recovery process. In the recovery consists of two different duration known as t a and t b, which is what we see here as the first half, this reverse recovery consists of an early recovery part where the current monotonically, keeps changing in one direction.

Then this is where the junction really starts to recover and the recovery is complete here. So, the start of recovery is the first part of the time and then completion of recovery is the second part of the time. And the charge collected during that process is the reverse recovery charge, you can see that the time a is about 48 nano second and time b is about 22 nano seconds.

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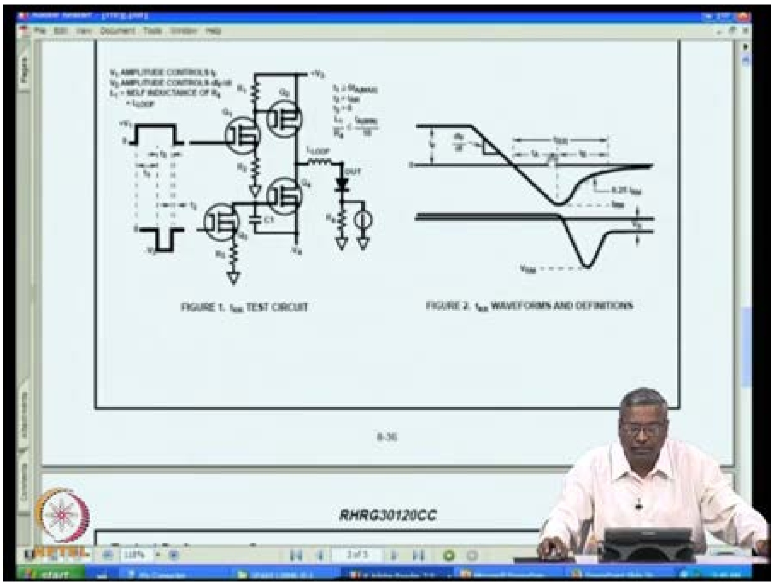

And you can see here is a and b are the two times that are designated here, this particular diode is specified as a soft recovery diode. So, that this recovery current the slope changes smoothly, there are some diodes where the slope changes very abrupt, they are called hard recovery diodes, this is a soft recovery diodes.

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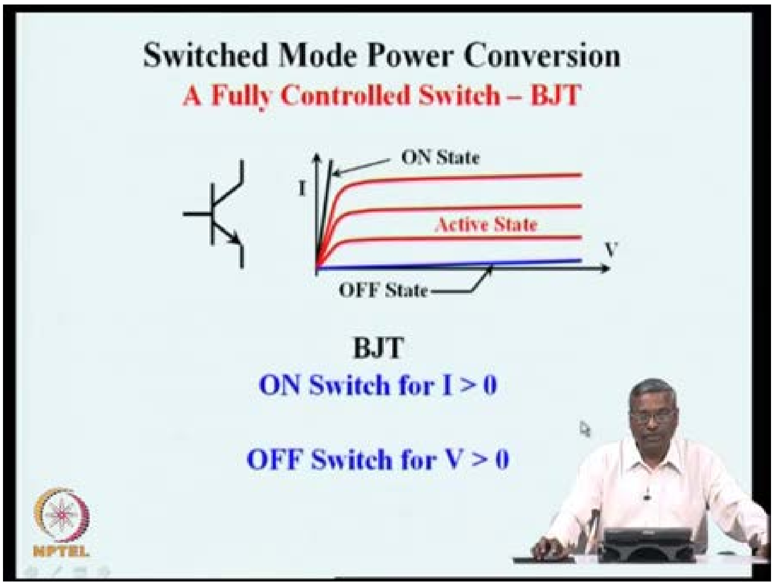

If we go on to the next type of switches these are the fully controlled switches, we had seen the diodes as uncontrolled switches. The S C R as semi-controlled switches, which as control only in one direction. Now, the first real switch belonging to the family of fully controlled switch is the bipolar junction transistor, this is a same as the junction transistor which is capable of operating for higher voltages and higher currents. It has three terminals the collector at the top, the emitter at this point collector and the emitter are the power terminals, and the base which is a controlled terminal and emitter.

Base and emitter form the control pair of terminals and emitter and collector form the power pair of terminals. And this device operation can be best understood by the characteristics that you see here, the operation of this device is given in the voltage current plane for different voltages, what is the kind of current that can flow in the device for various base currents. Base current is a parameter for which this is drawn, when there is no base current supplied the device as a voltage characteristics, which is very close to the voltage access a characteristics, which is very close to the voltage access.

The current through devices is very small voltage blocking is very large, this very typical of an off state switch at the other extreme, when the gate current is very large it is very large in relation to the required current for the collector to emitter. That is this end of the operating point in such a state, you will find the device can carry a very large amount of current with the very small voltage drop.

The V I characteristics are very close to the current access, and this is very typical of an on state switch. And in between you have the red color characteristics, which are the active state of the switch. When a transistor is used as an amplifier normally, this is a region in which operation is done and the base current is amplified, in the collector and the collector resistance will provide a voltage in a typical amplifier, this is the region in which the transistor will be operated.

The voltage across the device and current through the device will be quite large, and so there will be a large amount of power dissipation in the device, but in opposition to that kind of operation, in switched mode power conversion or in power converters. Whenever, we bipolar junction transistor it is used in the form of a switch, it has two states which is the off state and on state.

Off state is when base drive is completely cut off, on state is when base drive is maximum. So, the device in the on state will have a small voltage drop and large current passing, and device in the off state will have a small leakage current blocking a large voltage. And in the on state the B J T switch takes current only in the positive direction and similarly, in the off state the B J T switch it can block voltage only in the positive direction.

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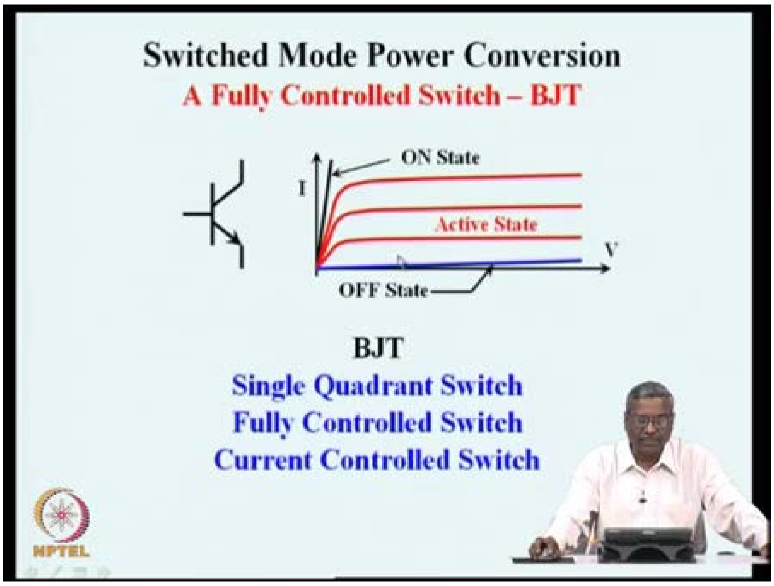

So, we might say that this is also a single quadrant switch it can block voltages only in one direction positive and it can pass current only in one direction, which is positive and effectively this is a single quadrant switch. The important difference is that this single quadrant switch, if you provide base current it will become on, if you do not provide base current it becomes off. So, it is capable of being controlled both in the on state and in the off state and it is a fully controlled switch, unlike a diode which is an uncontrolled switch, a transistor, a thyristor which is semi controlled switch, a transistor is a fully controlled switch.

Another important feature is that these characteristics the active states or moving from the off state to the on state is characterized by a large supply of current in the base symmetry circuit. So, the device is turned on by supplying a large current in the base to a meter. So, this is a current controlled switch so in the power conversion terminology a B J T can also be referred to this features being a single quadrant switch, being a fully controlled switch, and being a current controlled switch.

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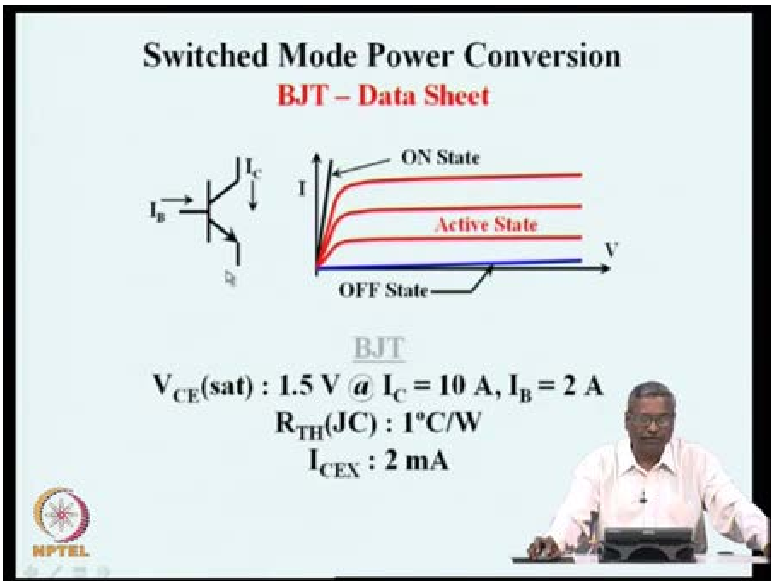

The data sheets of a B J T again is a store house of a lot of information, we will be able to see those details just now. When the device is operating in the on state it has a collector to emitter voltage, which is specified as V CE saturation that is the device has full base current. So, that it is instauration, in-saturation state the collector emitter voltage drop is very small and it can support a very large amount of a collector current, this is given as in this particular device 1.5 volts at a collector current of 10 amperes. And to keep this 10 amperes on in the saturation level, the base current required is 2 amperes in this particular case many of this features are seen from the data sheet.

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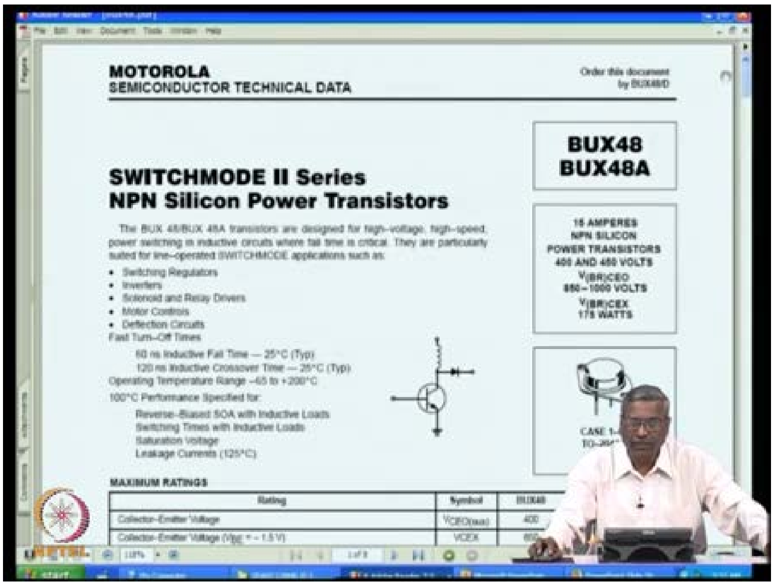

If we can see the data sheet of a device, which is specified as B U X 48 and B U X 48A these are power transistors, which were very popular nearly 20 to 30 years back, they are rated for you can see that the single slide specification says 400 and 450 volts for 48 and 48A. And the current can be 15 amperes on the collector and it is an N P N transistors, silicon transistor capable of operating with large power and the dissipation can be as much as 175 watts this relates to the capability of the package to handle power. The applications are given as switching regulators, invertors, drivers, motor controls deflections, circuits in T V, first turn off timers and so on. Several applications are given let us look at some of the important characteristics here.

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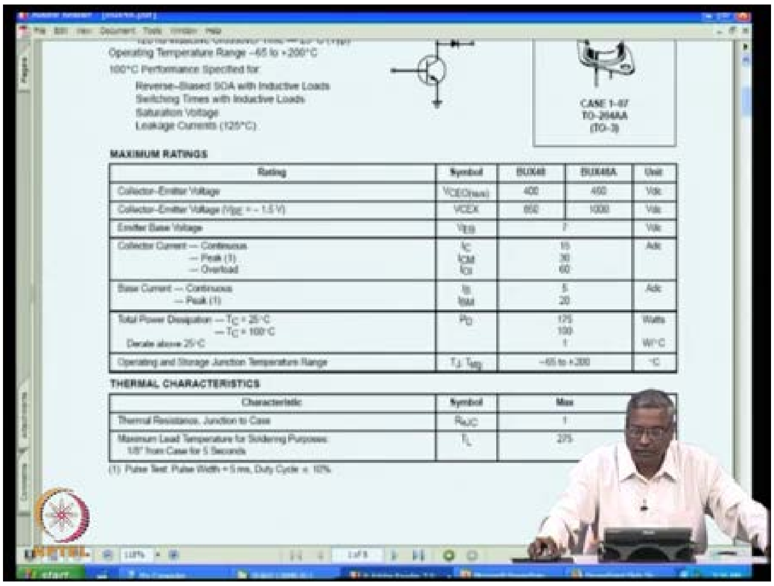
Operating Temperature Range −65 to +200°C
100°C Performance Specified for:
Reverse–Biased SOA with Inductive Loads
Switching Times with Inductive Loads
Saturation Voltage
Leakage Currents (125°C)

CASE 1-07
TO-204AA
(TO-3)

MAXIMUM RATINGS

Rating	Symbol	BUX48	BUX48A	Unit
Collector–Emitter Voltage	$V_{CEO(sus)}$	400	450	Vdc
Collector–Emitter Voltage (V_{BE} = −1.5 V)	V_{CEX}	850	1000	Vdc
Emitter Base Voltage	V_{EB}	7		Vdc
Collector Current — Continuous — Peak (1) — Overload	I_C I_{CM} I_{OI}	15 30 60		Adc
Base Current — Continuous — Peak (1)	I_B I_{BM}	5 20		Adc
Total Power Dissipation — T_C = 25°C — T_C = 100°C Derate above 25°C	P_D	175 100 1		Watts W/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	−65 to +200		°C

THERMAL CHARACTERISTICS

Characteristic	Symbol	Max
Thermal Resistance, Junction to Case	$R_{\theta JC}$	1
Maximum Lead Temperature for Soldering Purposes: 1/8" from Case for 5 Seconds	T_L	275

(1) Pulse Test: Pulse Width = 5 ms, Duty Cycle ≤ 10%.

So, what you will see at this point is one of the important characteristics, which is on state voltage.

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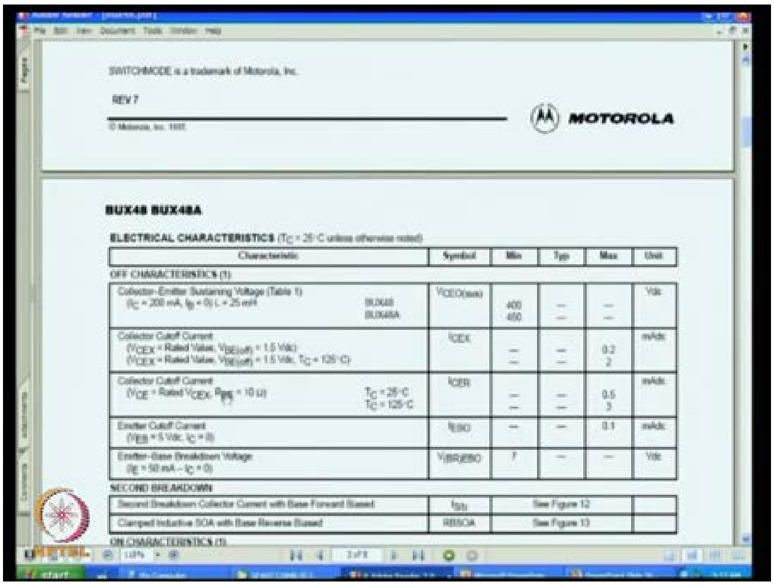

For example, there are characteristics which are given here as half characteristics, which for this particular blocking voltage, the collector current is as much as collector cut off current is about 2 mill amperes. Collector cut off current with emitter open circuit, emitter cut off current 0.1 mill ampere, this I C E R is the kind of current that flows in the device, when the base and emitter or terminated with the resistance of 10 ohm.

This one of the important specification for us, many times when we want to keep the device off, we will simply terminate with the resistor between base and emitter recommended by this number in which case, with rated voltage across the collector to emitter. The device will have a leakage current of 3 mill amperes that is what we see here, but if you can supply a negative bias to the base during the same condition, this current can be brought down further. This is about the off state characteristics, let us see if you have any on state characteristics, which is the next box that you see here.

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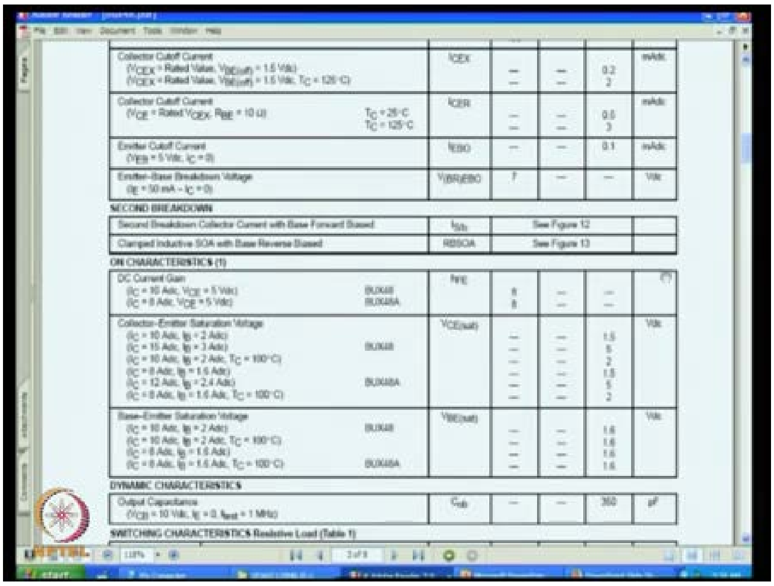

Characteristic	Symbol	Min	Typ	Max	Unit
Collector Cutoff Current (V_{CEX} = Rated Value, $V_{BE(off)}$ = 1.5 Vdc) (V_{CEX} = Rated Value, $V_{BE(off)}$ = 1.5 Vdc, T_C = 125°C)	I_{CEX}	— —	— —	0.2 2	mAdc
Collector Cutoff Current (V_{CE} = Rated V_{CEX}, R_{BE} = 10 Ω) T_C = 25°C T_C = 125°C	I_{CER}	— —	— —	0.5 3	mAdc
Emitter Cutoff Current (V_{EB} = 5 Vdc, I_C = 0)	I_{EBO}	—	—	0.1	mAdc
Emitter-Base Breakdown Voltage (I_E = 50 mA - I_C = 0)	$V_{(BR)EBO}$	7	—	—	Vdc
SECOND BREAKDOWN					
Second Breakdown Collector Current with Base Forward Biased	$I_{S/b}$	See Figure 12			
Clamped Inductive SOA with Base Reverse Biased	RBSOA	See Figure 13			
ON CHARACTERISTICS (1)					
DC Current Gain (I_C = 10 Adc, V_{CE} = 5 Vdc) BUX48 (I_C = 8 Adc, V_{CE} = 5 Vdc) BUX48A	h_{FE}	8 8	— —	— —	—
Collector-Emitter Saturation Voltage (I_C = 10 Adc, I_B = 2 Adc) (I_C = 15 Adc, I_B = 3 Adc) BUX48 (I_C = 10 Adc, I_B = 2 Adc, T_C = 100°C) (I_C = 8 Adc, I_B = 1.6 Adc) (I_C = 12 Adc, I_B = 2.4 Adc) BUX48A (I_C = 8 Adc, I_B = 1.6 Adc, T_C = 100°C)	$V_{CE(sat)}$	— — — — — —	— — — — — —	1.5 5 2 1.5 5 2	Vdc
Base-Emitter Saturation Voltage (I_C = 10 Adc, I_B = 2 Adc) BUX48 (I_C = 10 Adc, I_B = 2 Adc, T_C = 100°C) (I_C = 8 Adc, I_B = 1.6 Adc) (I_C = 8 Adc, I_B = 1.6 Adc, T_C = 100°C) BUX48A	$V_{BE(sat)}$	— — — —	— — — —	1.6 1.6 1.6 1.6	Vdc
DYNAMIC CHARACTERISTICS					
Output Capacitance (V_{CB} = 10 Vdc, I_E = 0, f_{test} = 1 MHz)	C_{ob}	—	—	350	pF
SWITCHING CHARACTERISTICS Resistive Load (Table 1)					

See this tells you for the device which is BUX 48, the saturation voltage is 1.5 volts between collector and emitter, for a condition corresponding to 10 amperes of collector current and 2 amperes of base current. In order to pass 10 amperes in the collector, you need a base current of 2 amperes then under that condition the collector voltage is limited to 1.5. If you go to the full current, the rated current of the device which is almost 16 amperes, 15 amperes you will find the voltage drop is quite large.

At 15 amperes the base current will be 3 amperes, and the saturation voltages is 5 volts here. Now, this is an indication normally this is an indication of how much base drive one has to provide in order to keep it as a satisfactory on switch. There are a dynamic performance characteristics are which, we will see a little later. The thermal resistance is 1 degree centigrade per watt, this is an important specification because this will tell us how much power that can be successfully, taken out from the device. So, that it can operate at the at the power level at which it has been specified, it is given here that it can work up to a dissipating power level of 175 watts, if the case is at 25 degrees, 100 watts if the case is at 100 degrees and so on.

And the operating and storage junction temperature range is up to 200 degrees, it is possible to go to a peak junction temperature of 200 degree centigrade, and still have the device functioning satisfactorily. I had put here some of the essential numbers like the thermal resistance 1 degree centigrade per watt, the leakage current which is 2 mill amperes saturation voltage, which is 1.5 volts at 10 ampere with a base drive of 2 amperes. So, these operating points could be somewhere here 10 amperes current with 1.5 volts and 400 volts and 2 milli amperes. So, some of the on state and off state and we never operate a switch in its active region, mainly because the power dissipation the active region is very large.

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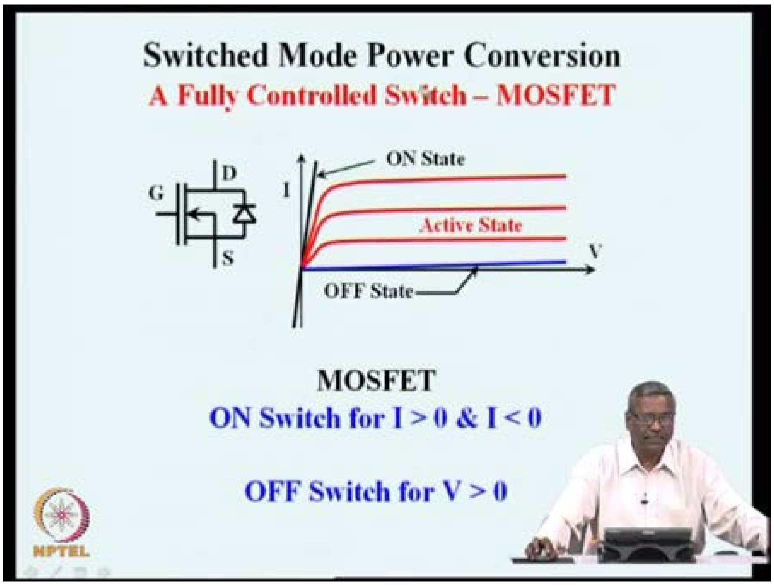

The next in the family of fully controlled switch is the MOSFET, metal oxide semi conductor fill defect transistor. The characteristics are very similar with one addition, the device has a built diode which is in the opposite polarity. So, this diode can conduct current in the negative direction, any current in the negative direction this from source to drain will pass through the diode, which is this part. And any current which is drain to source is this section provided gate is adequately, positively biased and if the gate is not adequately positively biased, the device will be in the cut off region which is off state. And if this is in the active region then you could operating point somewhere here.

So, as power conversion of switch mode power conversion applications, our operating points will be limited to the on state, off state and in the reverse conducting state. A MOSFET as 3 state on state, which is when current is flowing from D to S and the gate is given a voltage which is positive with respect to source. Then the reverse conducting state, when the external current is flowing from source to drain, no control action is taking place in the device.

Then the forward blocking state is when gate is either at the same potential as the source, or gate is at a negative potential with respect to the source, in which case no current flows through the device, and in the device can block large positive voltages. So, it is an on switch for I greater than 0 as well as I less than 0 of switch it can be used for V greater than 0. So, you see that it can block and pass currents which are block currents in positive and negative direction, block voltage only in positive direction. So, this switch is a 2 quadrant switch.

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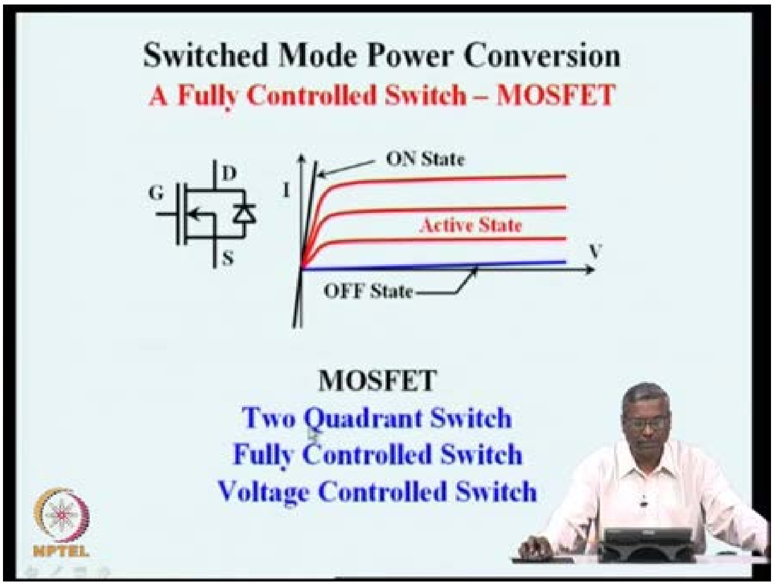

And it is a fully controlled switch, you can move from on state to off state, off state to on state, on state to off state by controlling the bias that is given to the gate with reference to the source. The gate and the source form the control terminal pair, and the source and the drain form the power terminal pair. And this is a voltage control switch unlike bipolar junction transistor, a MOSFET field defect transistor turns off or on depending on the voltage of the gate with respect to the source.

So, in effect we indentify a MOSFET with these features. The 2 quadrant switch, 2 quadrant because the current can be in both positive and negative direction and voltage is only in one direction. And it is a fully controlled switch because through the gate you can make it on, or off. Voltage control switch because the control function is achieved by keeping the gate at a voltage with respect to these source.

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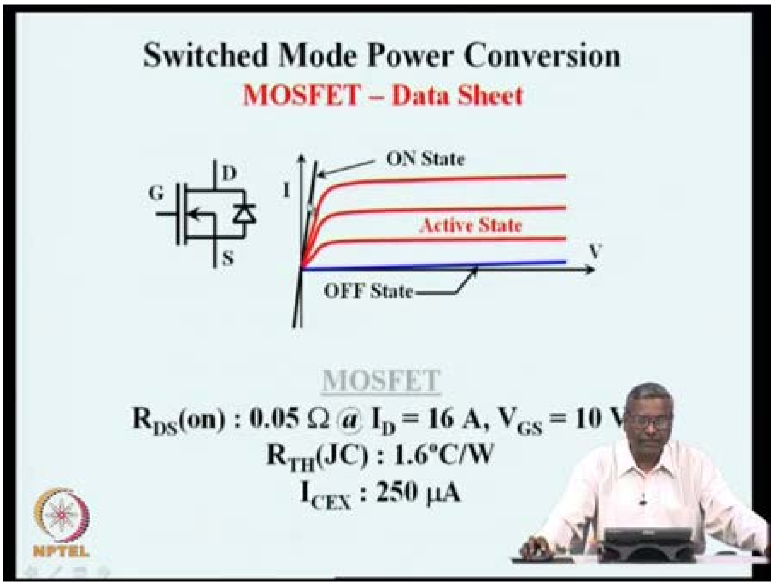

The MOSFET characteristics as we had seen here and the essential characteristics, which are specified here as R DS on in the on state unlike a B J T, a bipolar junction transistor in the on state as a saturation voltage drop we see is sat, but a MOSFET in the on state behaves just like a resistor. So, it is specified as on state resistance in this particular device, we will see the data sheet in a moment.

The on state resistance is 0.05 ohm when it is carrying a current of 16 amperes and when the gate is biased 10 volts with reference to the source when V GS is 10 volts positive and with the drain is carrying a current of 16 amperes, the R DS on or the on state resistance of this device is 0.05 ohm. And the device has the same kind of thermal resistance junction to case, which is given in degree centigrade per watt, which is useful to design the heat dissipation mechanism or heat management mechanism. The leakage current is about 250 micro amperes let us look at the data sheet of this device.

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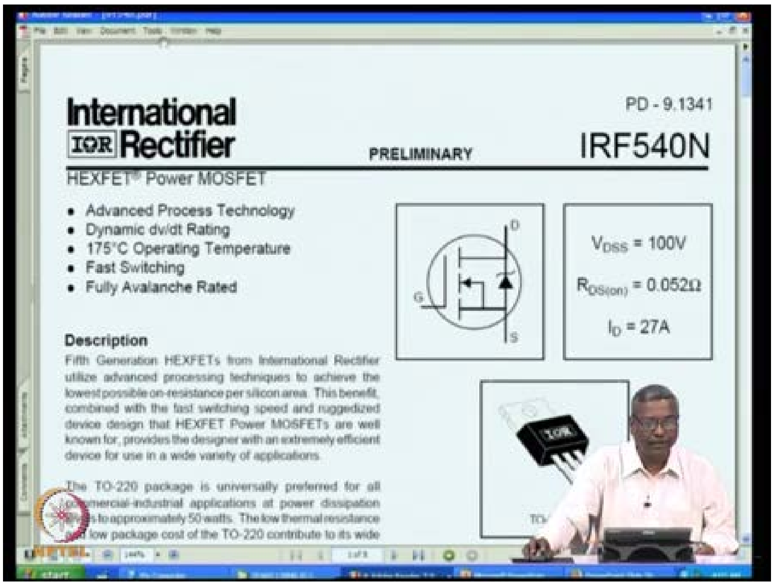

This is made by a manufacturer international rectifier IRF540 is the name of this device, and this is N channel MOSFET, and the single lines on this is 100 volts 0.52 ohm resistance on state. And a current of 27 ampere, drain current of 27 ampere. So, it is capable of conducting up to 27 amperes of current, blocking up to 100 volts of voltage with an on state resistance of 0.05, 2 ohms when it is kept on.

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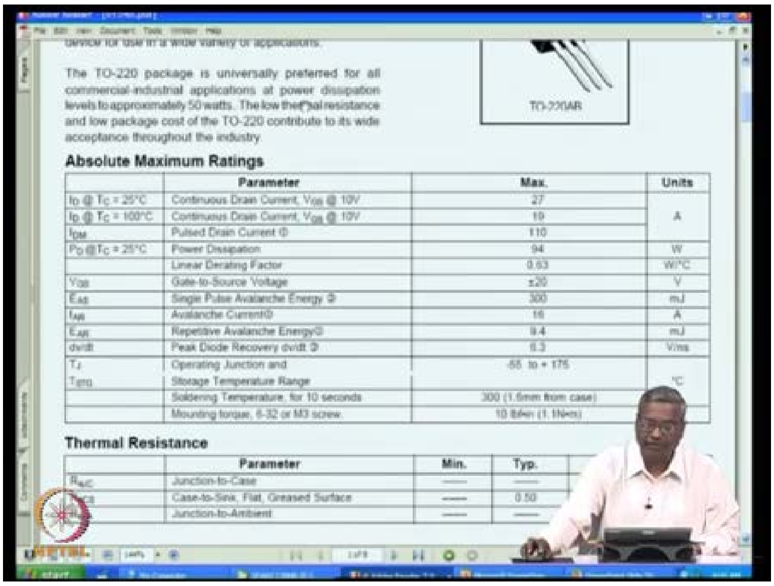

Now, many of the data as we see here will be quite helpful. For example, at a junction k temperature of 25 degrees, this device can successfully carried 27 ampere when the V g s get to source is kept at a bios voltage of 10 volts at a case temperature of 100 degrees at case temperature 100 degree centigrade. The same device under the same operating condition can carry a current of only 19 amperes, this is because as temperature goes higher the R DS on increases, and because of that dissipation in the device goes up.

Now, the device can normally use for pulsed current this is another positive advantage that because it has a large pulse current rating nearly, four times the pulse four times the maximum continuous current rating, in comparison with B J T a MOSFET is even more rugged, it is more capable of carrying pulse current which are almost four times more than the rated continuous drain current. The gate to source voltage this is the control voltage one which, one should understand the can be up to a maximum of plus 20 volts or minus 20 volts this is something which, when exceeded will result in damage to the gate.

So, normally their recommended numbers will be about 12 volts plus to keep the device on and about 12 volts minus to keep the device off, many of these specifications can be seen in the data sheet at different points. And you see from here that the junction can go up to a maximum operating temperature of 175 degree centigrade. We will see that this number for B J T could be around 150 degree, for diodes it could be 200 degrees, for MOSFET it could be 150 or 175 degrees and so on. And many data sheets will tell what is the minimum temperature up to which these can be successfully used, and maximum temperature up to which it can be successfully used.

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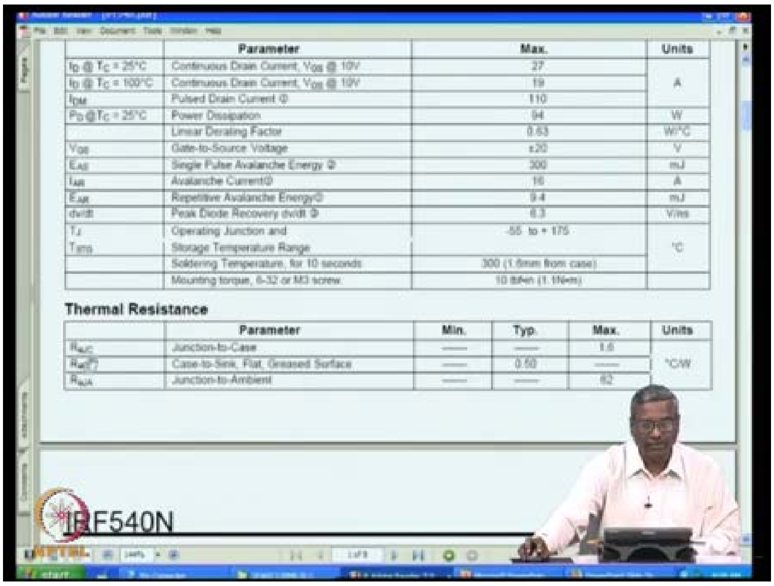

The thermal resistance is R theta junction to case is specified as 1.6 degree centigrade per watt, there are few other numbers given here junction to case, case to heat sink junction to ambient. If you do not use any heat sink then the thermal resistance of junction to ambient, you can see a 62 degree centigrade per watt. So, if you simply dissipate about 2 watts, this will have a temperature wise about 125 degrees. So, you can see that even though this device is capable of dissipate 94 watts, when it is properly designed with a heat sink, without heat sink it cannot even dissipate 2 watts see the difference.

About 100 watts you can dissipate if you have a proper heat management circuit, or heat sink and without heat sink it cannot even dissipate 2 watts, this is something which one should be careful about even when you are building circuits, and testing them. Testing them without heat sink as this great penalty, the power dissipation is not even 2 percent of the power dissipation, when it is with the heat sink. So, many times we will lose a device because the heat sink is not connected and even at a very small just 2 percent of power level, the device reaches large junction temperature gets damaged, this is something one has to be careful about.

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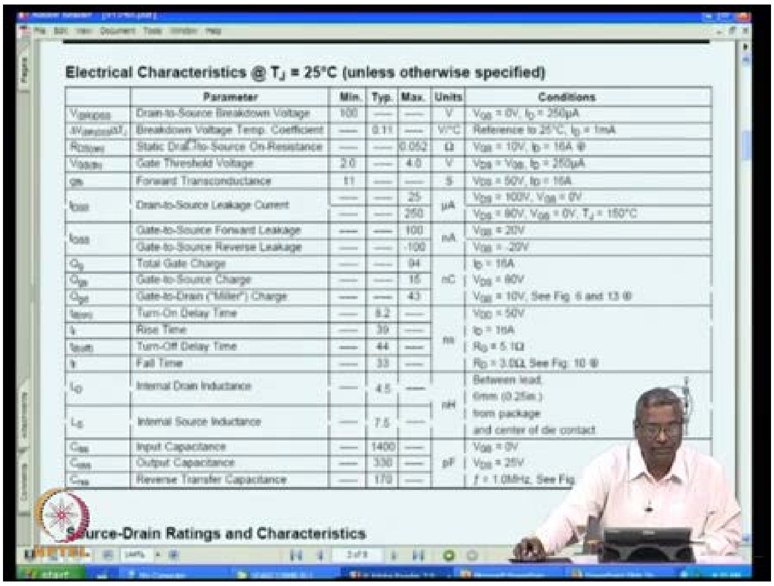

Now, if we go to the rest of this specification, you see here R DS on this is an important specification, which tells you what is on state resistance when V GS is so much and I D is now, this is at a junction temperature of 25 degrees, when nothing is specified 25 degrees applies and you can see that the same data sheet will also give another important spike which is the dependence of R DS on the junction temperature.

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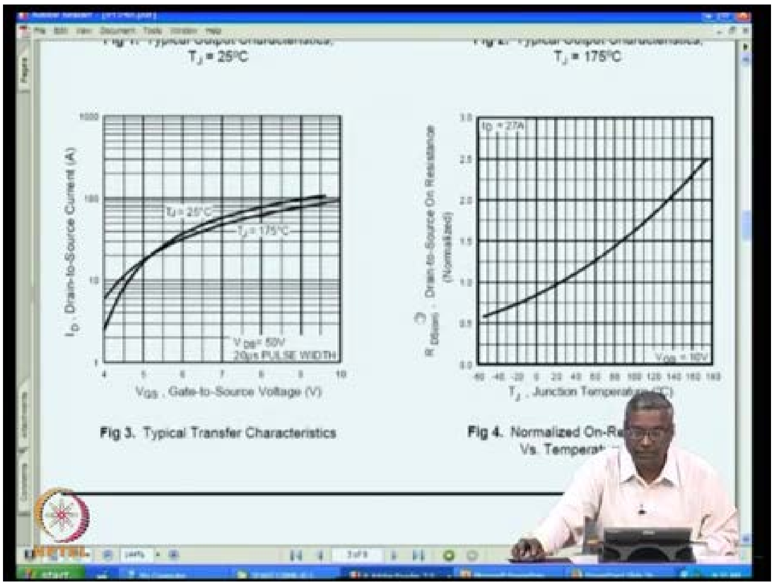

R DS on drain to source on state resistance normalized with respect to junction temperature. So, what you see here is at 25 degree centigrade, whatever is the R DS on given is the multiplying factor is 1, but if you go to 125 degrees junction temperature, the multiplying factor is almost 2. That means, this device if the junction is operating at 125 degrees will have an on state resistance of almost double this number instead of 0.052, it will have 0.1 ohm, this is something which one has to keep in mind. Many of the other numbers important study state numbers are given.

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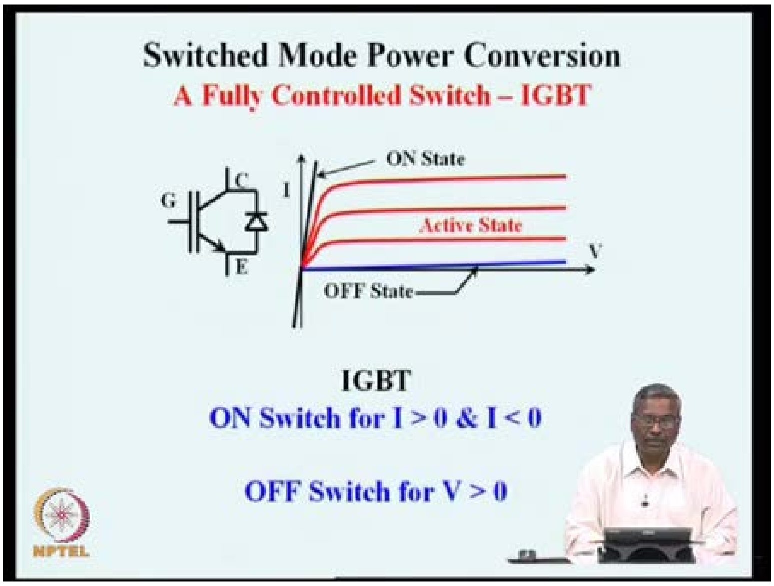

And the third in the family of fully controlled switch is the I G B T insulated gate bipolar transistor. This device is really a hybrid of MOSFET and B J T, the power circuit is very similar to B J T and the control end is very similar to a MOSFET. So, it is termed as the terminal are marked as the collector, and emitter on the power side at gate on the control side, this gate and emitter form the control terminal pair and collector and emitter form the power terminal pair, and like a MOSFET this is also has a diode anti parallel diode, which will make the current flow both in positive and negative direction. And if you do not provide enough bias for the gate, the device will be off and this is the off state.

So, the device can carry current both in positive and negative if it is correctly bias and if it will be if the off state with positive voltage across the device, when the gate is at negative voltage with respect to the emitter. So, just like a MOSFET this is also a 2 quadrant switch, it has 2 quadrants switch of operation because current can be both plus and minus, voltage is only plus.

So, effectively it is a 2 quadrants switch. It is the fully controlled switch because by controlling the gate voltage with reference to the emitter, it is possible to keep it on or off. So, you can move from on state to off state, off state to on state by changing the voltage on the gate, it is fully controlled. And the control feature is by the voltage on the gate with reference to the emitter and so this is also a voltage controlled switch.

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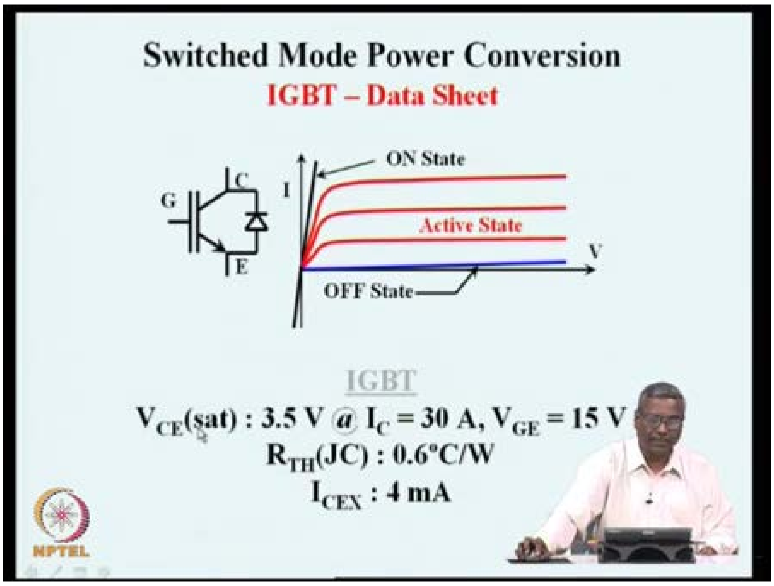

I G B T has because the power circuit is very similar to B J T as a V CE sat or saturation collector emitter voltage, for a given current with a given get to emitter bias voltage. Many times MOSFET's are devices, which are preferred for lower voltage up to 60 volts are 100 volts and I G B T are preferred devices for higher voltages 600 volts or above of course, there are MOSFET available even up to 800 volts or 1000 volts, but preferably MOSFET are used in low voltage, high current circuits. And I G B T are preferred in high voltage low current as well as high current devices. Some of the key specifications that you see here are saturation voltage, on state current, control voltage, thermal resistance and off state current, which is the leakage current.

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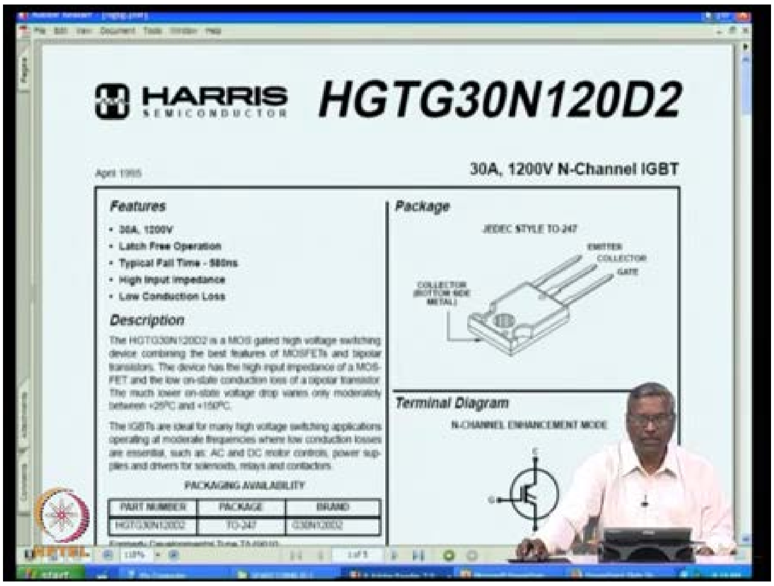

From the data sheet one can see all these characteristics, this is a 30 ampere, 1200 volts N channel I G B T device.

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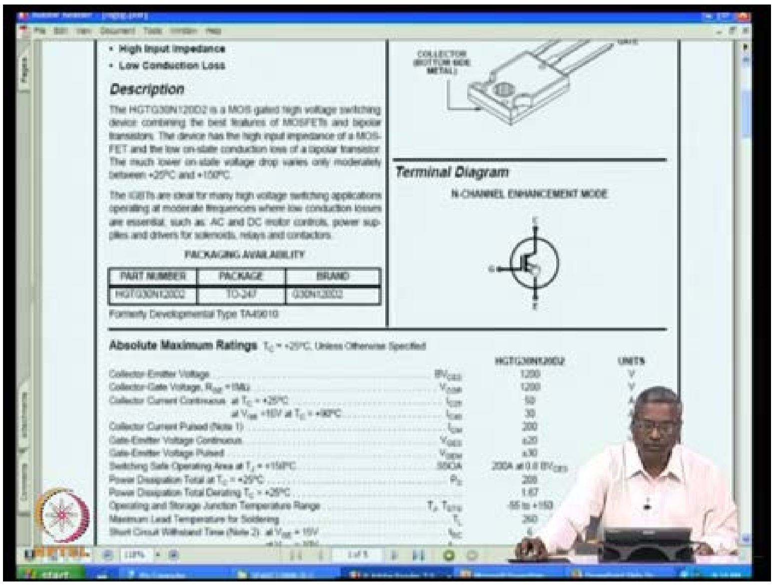

The symbol is very similar to a B J T on the power site, and a MOSFET on the control side. Get emitter in the control pair collect emitter is the power pair, this particular device is rated up to 1200 volts and a current of 50 amperes. And the thermal resistance is 1.67 or our dissipation thermal resistance will be probably bottom. Degree c per watt this the thermal resistance 0.6 degree centigrade per watt normally, when you are reading a data sheet it good to read from the dimensions, the important things. So, that you will be able to 0 in on where, what is given the on state voltage and the off state current are important specifications, let see where those are given.

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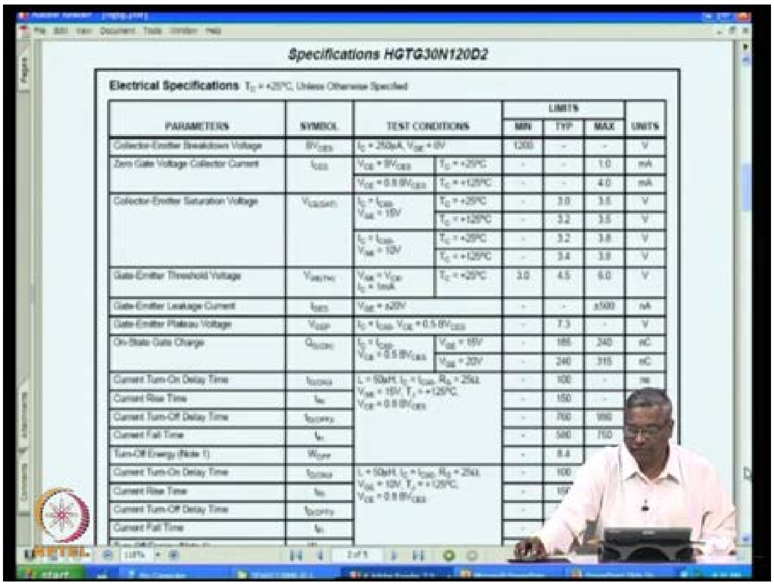

Specifications HGTG30N120D2

Electrical Specifications T_C = +25°C, Unless Otherwise Specified

PARAMETERS	SYMBOL	TEST CONDITIONS		LIMITS MIN	TYP	MAX	UNITS
Collector-Emitter Breakdown Voltage	BV_{CES}	I_C = 250μA, V_{GE} = 0V		1200	-	-	V
Zero Gate Voltage Collector Current	I_{CES}	$V_{CE} = BV_{CES}$	T_C = +25°C	-	-	1.0	mA
		V_{CE} = 0.8 BV_{CES}	T_C = +125°C	-	-	4.0	mA
Collector-Emitter Saturation Voltage	$V_{CE(SAT)}$	$I_C = I_{C90}$, V_{GE} = 15V	T_C = +25°C	-	3.0	3.5	V
			T_C = +125°C	-	3.2	3.5	V
		$I_C = I_{C90}$, V_{GE} = 10V	T_C = +25°C	-	3.2	3.8	V
			T_C = +125°C	-	3.4	3.8	V
Gate-Emitter Threshold Voltage	$V_{GE(TH)}$	$V_{GE} = V_{CE}$, I_C = 1mA	T_C = +25°C	3.0	4.5	6.0	V
Gate-Emitter Leakage Current	I_{GES}	V_{GE} = ±20V		-	-	±500	nA
Gate-Emitter Plateau Voltage	V_{GEP}	$I_C = I_{C90}$, V_{CE} = 0.5 BV_{CES}		-	7.3	-	V
On-State Gate Charge	$Q_{G(ON)}$	$I_C = I_{C90}$, V_{CE} = 0.5 BV_{CES}	V_{GE} = 15V	-	185	240	nC
			V_{GE} = 20V	-	240	315	nC
Current Turn-On Delay Time	$t_{D(ON)I}$	L = 50μH, $I_C = I_{C90}$, R_G = 25Ω, V_{GE} = 15V, T_J = +125°C, V_{CE} = 0.8 BV_{CES}		-	100	-	ns
Current Rise Time	t_{RI}			-	150	-	
Current Turn-Off Delay Time	$t_{D(OFF)I}$			-	700	900	
Current Fall Time	t_{FI}			-	500	750	
Turn-Off Energy (Note 1)	W_{OFF}			-	8.4		
Current Turn-On Delay Time	$t_{D(ON)I}$	L = 50μH, $I_C = I_{C90}$, R_G = 25Ω, V_{GE} = 10V, T_J = +125°C, V_{CE} = 0.8 BV_{CES}		-	100		
Current Rise Time	t_{RI}			-	[illegible]		
Current Turn-Off Delay Time	$t_{D(OFF)I}$			-			
Current Fall Time	t_{FI}			-			

For example, the leakage current is about 4 milli ampere at 80 percent of the rated voltage at a case temperature of 125 degrees that is what this line is specifying. When the V c is sat or the on state voltage maximum voltage is 3.5 to 3.8, for a current rating off I C 90 that is when the case is at 90 degrees. Whatever is a current rating with the gate emitter voltage 15 or gate emitter voltage 10. So, when the gate emitter is based at a lower voltage, you can see that the saturation voltage is higher indicating that the power dissipation is more in the device. The product of the on state voltage and on state current will be the power dissipation, and that as to be accounted for in the thermal design of the switch.

Now, let us see some compounds switches we have already seen uncontrolled switches, semi controlled switches and fully controlled switches, but all these where either single quadrant or 2 quadrant switches. It is possible to connect 2 S C R back to back. So, that these specification now or the V I characteristics now, covers the entire 4 quadrant, you can pass current in positive and negative direction. And you can block voltage positive and negative voltages.

So, this device 2 thyristors connected back to back across 2 terminals and anti-parallel S C R’s. They are referred to as anti-parallel connected S C R’s is a 4 quadrant switch, it is again a semi controlled switch, you can only turn on the device you will not able to turn off, unless the current goes to the 0, the device will not turn off and it is the pulse triggered switch, there is no need to continuously keep it on a pulse to the gate is enough to turn on the device.

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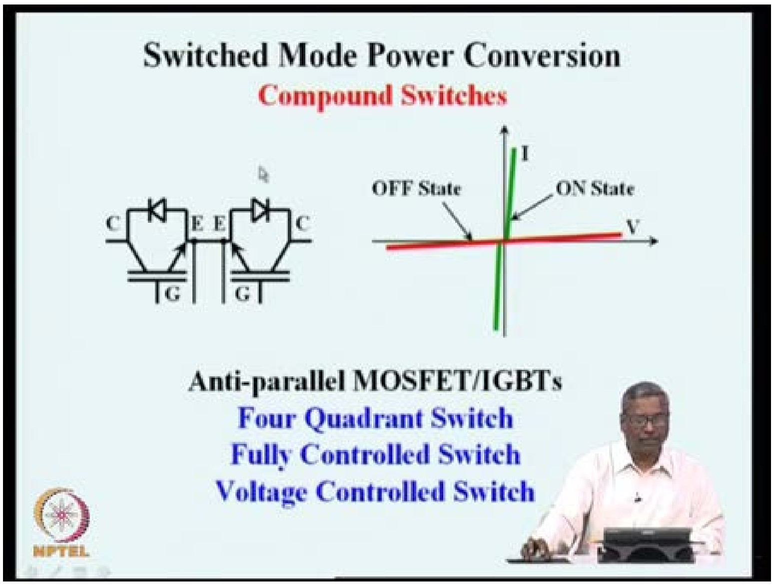

This is an another compounds switch, which is a 4 quadrant switch fully controlled, voltage controlled switch anti-parallel MOSFET or I G B T's both MOSFET or I G B T can be used in this. You can see that two devices are now connected in series unlike the thyristors, which two were connected in parallel to form a compound switch, here 2 devices are connected in series, to form a compound switch. The current can when the device on the right hand side is on, current can flow through this in the from right to left. And when the left hand side device is on, current can flow from left to right. So, it is possible to support current both in positive and in negative direction.

And similarly, it is possible to support block the voltage both in positive and negative direction by selectively turning on or turning off, these two controlled devices. So, this is a compound switch, it is equivalent to an ideal switch which can conduct current both in positive and negative direction, block voltages both in positive and negative voltages. The non ideal feature of this switch is that you will have voltage drops, while current is flowing and when voltages is block, there will be some leakage, but as I said before the leakage performance is very close to the ideal, you will find that blocking currents are almost 0. The on state voltages will be probably a fraction of 1 percent or so half a percent or even less, the blocking loss will be even smaller.

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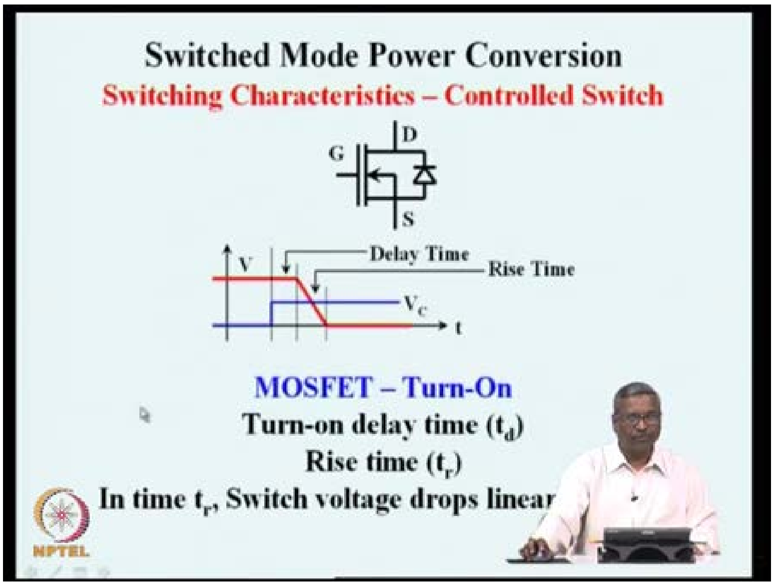

Now, we come to the next set of characteristics for the switches, which are the dynamic characteristics. See whenever you have a controlled switch, a fully controlled switch we know that the switch can be turned on or turned off through the control terminals. For example, this MOSFET can be turned on by charging the gate or by discharging the gate. So, if you see this blue line here which is a control voltage that is the charge that we give to the gate.

If this blue line represents the gate voltage then it is possible to identify, what are the performance features of a MOSFET switch, when it comes to switching performance. So, these are switching characteristics of a controlled switch, you will notice that whenever a switch is on, the voltage across that has to be 0, but here this the time when the switch is off V c is 0 and the voltage device is blocking the voltage, decided by the circuit voltage, but as soon as you have given a command to turn on the device, for some duration nothing happens and this is called the delay time.

During the delay time, the device does nothing internally something happens, and after that the voltage drops from the blocking state to the conduction state almost linearly, in a time know as rise time and we call that as the rise time. The turn on of the device has two components a delay time when nothing a happens after the command is given, and then a rise time when the voltage linearly drops to 0. So, we call these time as t d delay time and t r rise time, in time t r the switch voltage drops linearly to 0.

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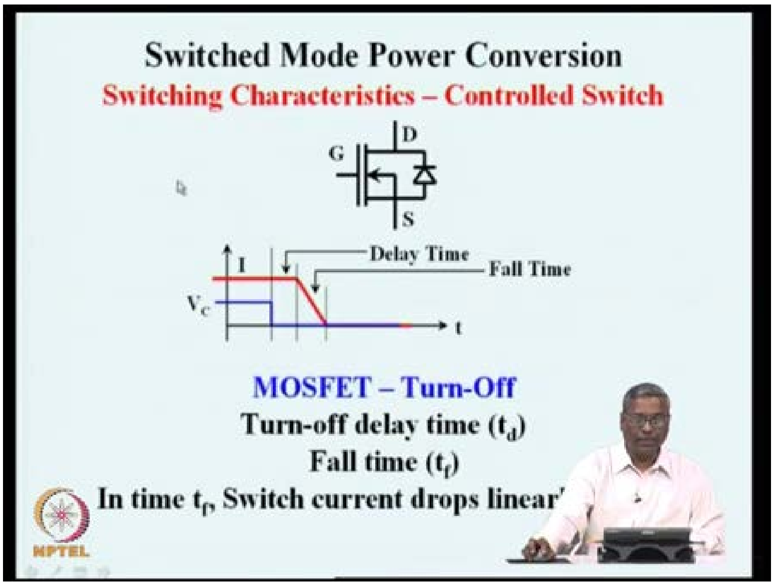

The controlled switch in the turn off characteristics also indicates a very similar performance feature, this the instant when we decide that the device will be switched off. There is a delay time when nothing happens, the current continues to flowing the device. And then there is a duration when the current linearly drops to 0, in the off state a device current has to be 0, in the on state device current is decided by the external circuit. So, this moment of passing current to zero current takes place in a time known as fall time. And that time follows the delay time.

So, from the time command is given to switch off the device nothings happens during the delay time, which is known as t d turn of delay time. And after that during the fall time t f, the current drops down to 0. This is one of the models for the switching characteristics of most of the controlled switches whether, it is a MOSFET or an I G B T or a B J T all of them exhibit a delay time and a switching time, switching time is the fall time in the case of switch off, rise time in the case of switch on.

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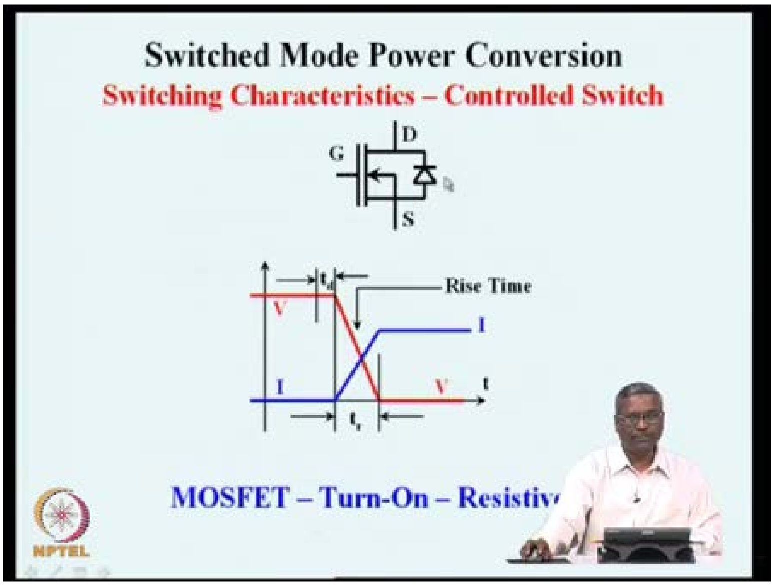

If we switch a resistive load with a controlled switch, you can see that after the command is given for a delay time nothing happens, after that as the voltage drops will load current increases. And this drop in voltage rise in current or almost synchronized because the load is purely resistive, it does not have any dynamic characteristics. So, the device dynamic characteristics is just simply carried on to the load, as the voltage is dropping the current is rising. And this is the turn on performance of a resistive load a MOSFET under resistive load. So, during the rise time the voltage of the device drops and the current during that time rises.

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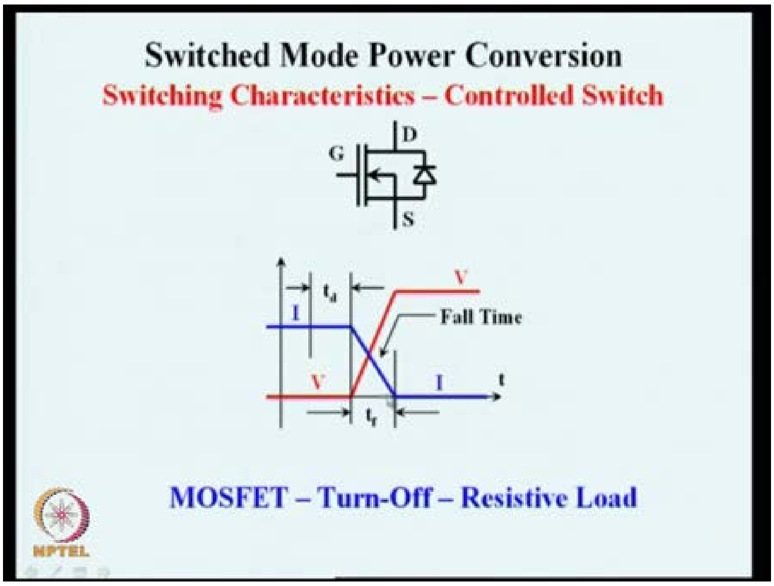

The turn off characteristics also is very similar, but the time now is called the fall time. During the fall time current falls linearly to 0 and the voltage across the device rises linearly to the full voltage. Now, in the case of resistive load, this drop in the current and the rise in the voltage whether, it is turn off or drop in the voltage and rise in the current in the case of turn on, both are straight lines is a very simple model and for resistive load this is true.

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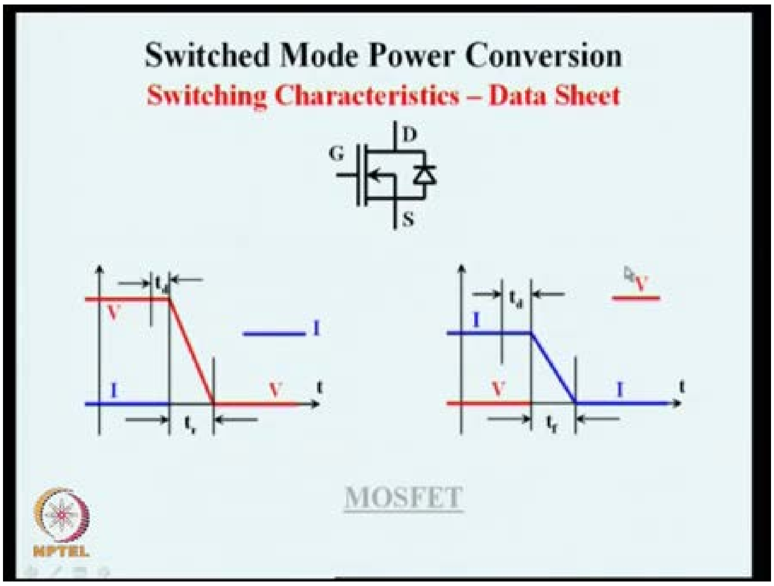

But in general, if the load is not resistive the turned on characteristic only one part is defined by the switch that is the drop in voltage to 0, in rise time is define by the switch. Similarly, in the turned off drop in current during the fall time from the full current to 0 current in t f linearly is defined, but how the current will rise how the voltage will rise during turn off, how the current will rise during turned on is really load dependent, is dependent on the external circuit. If the external circuit is resistive this also will follow a straight line which we had seen before, but if the external circuit is not resistive it will be something different you will see it in a moment. Now, let us see the dynamic characteristics of the MOSFET as it is given in the data sheet.

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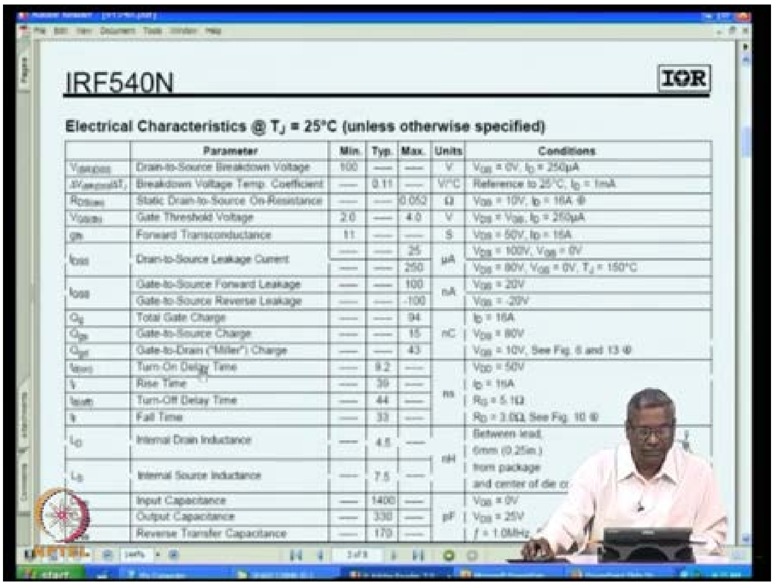

You can see that these 4 here t d on, t r t d off, t f or the times that I had mention you can see for this device, when the switching is done at 50 volts for a current of 16 amperes with gate resistance of 5.1 ohm with the drain resistance of 3 ohm in order to control the current, 50 volts by 3 is roughly 16 amperes. So, with this kind of a load and control characteristics, it turn on delay time is 8 nano seconds, 8.2 nano seconds. Turn off delay time is 44 nano seconds.

This again very typical, the device delay time during turn on is always very much smaller than the delay during turn off, the turn on delay time will be normally a small fraction of the turn off delay time, but during the delay time as we had seen, no change in voltage or current is taking place. So, that is not really very important accept for the delay that is introduced. There is no power dissipation during that time.

The rise time and fall time are merely equal whether, you are moving from on to off or off to on 39 nano second and 33 nano second are merely equal, this also will be very typical in most switches that rise time and fall time or of the same orders of magnetitude, but the delay time on delay time normally will be very small compare to off delay time. There are many other things, which we will come to know as we start designing systems later on in the applications part of this, but this kind of an on state delay time, rise time, off state, delay time, fall time these are all things one should keep in mind when we are trying to use it for higher and higher switching frequencies. I was mentioning that the current rise during on, and voltage rise during off is decided by the external circuit.

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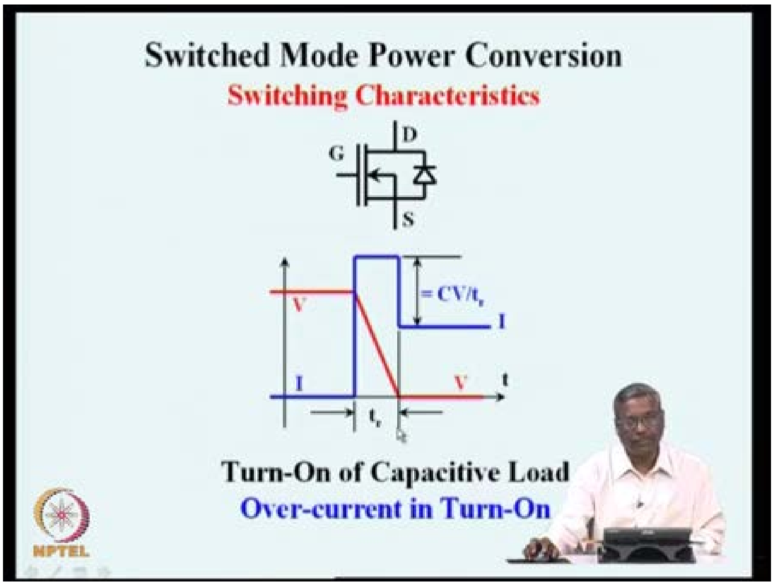

So, let us see how this external circuit determines these characteristics and whether, it is good or bad. Now, when you are turning on a capacitive kind of circuit because a voltage across the device falls linearly, you know that the capacitive current is C times d v by d t. So, this linear drop in voltage will give rise to an additional current of C times d v by d t, C times full voltage divided by full time. So, C V by t r will be the additional current in the switch apart from the load current, if it was a resistive load it will jump to load current and stop here. If it is a capacitive load of value C then it is possible that the current switched on is much higher than the load current. So, turn on of capacitive load results in over current during turn on, this is something important to known.

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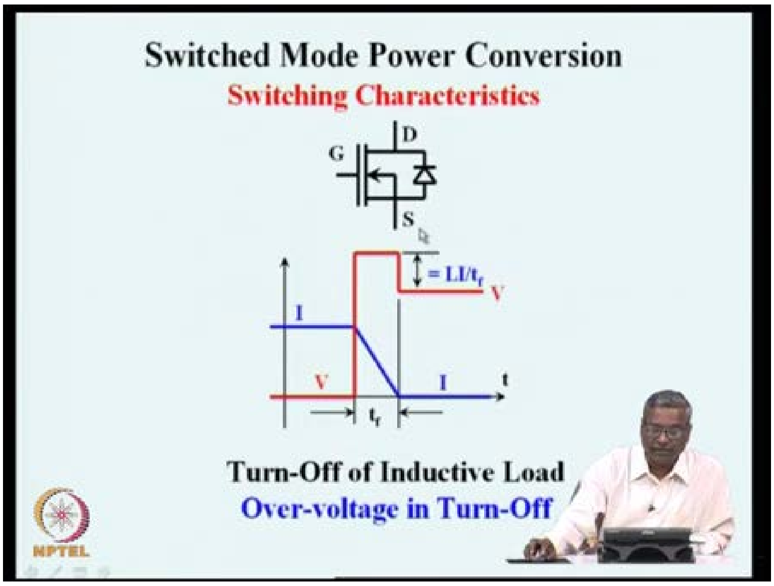

The counter part of that is whenever you turn off an inductive load, you know that in there inductance if the current is changed with the rate of change of current, the voltage across the inductor will be l b i by d t. So, if we have a load which is inductive, the voltage across that inductive, part of the load will be l into d i by d t which is I divided by t i by t f. So, this is the additional voltage which will come across the device the other than the circuit voltage. So, you can say that turn off of an inductive load results in over voltage, turn on of a capacitive load is results in over current, these are dual properties.

So, whenever a device is being turned off inductive load is more hazardous, and whenever a device is being turned on capacitive load is more hazardous. The other side of that is if you are turning on an inductive load, it always better because the inductance will not allow the current to rise very fast. So, turning on an inductive load is less hazardous compare to turning on a capacitive load. And similarly, turning off an inductive load is less hazardous compare to turning off an inductive load.

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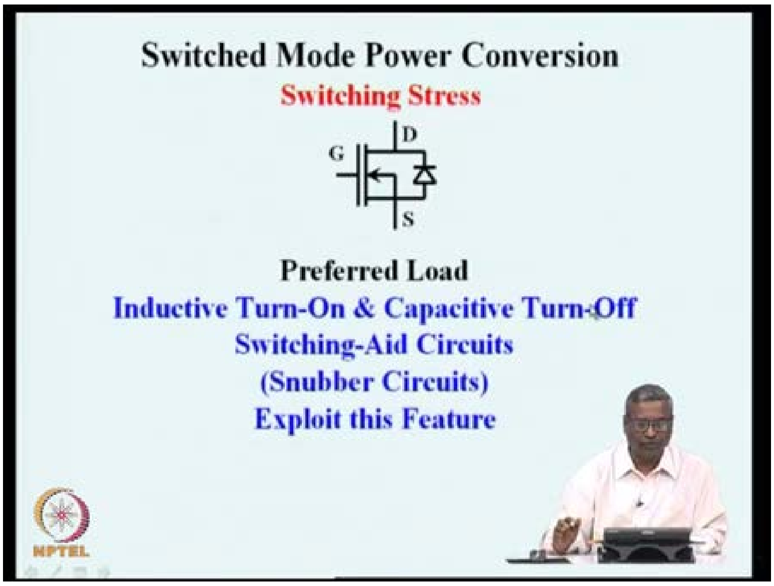

So, in general we would prefer the load to have inductive characteristics during turn on, and capacitive characteristics during turn off. In general this not really possible most loads will have either a nature of an inductance, or resistance or capacitance. So, if you really wish to have this preferred load characteristics, it is necessary to add additional circuits to the switch, which are known as switching aid circuit.

And these circuits are also called as snubber circuits and they are called capable of exploiting this feature, they will at components in the circuits, in such a way that during the small turn on period or during the small turn off period, the circuit will behave as if it is either an inductance or a capacitance, and that helps in making sure that they are no over currents during turn on and there are no over voltages during turn off.

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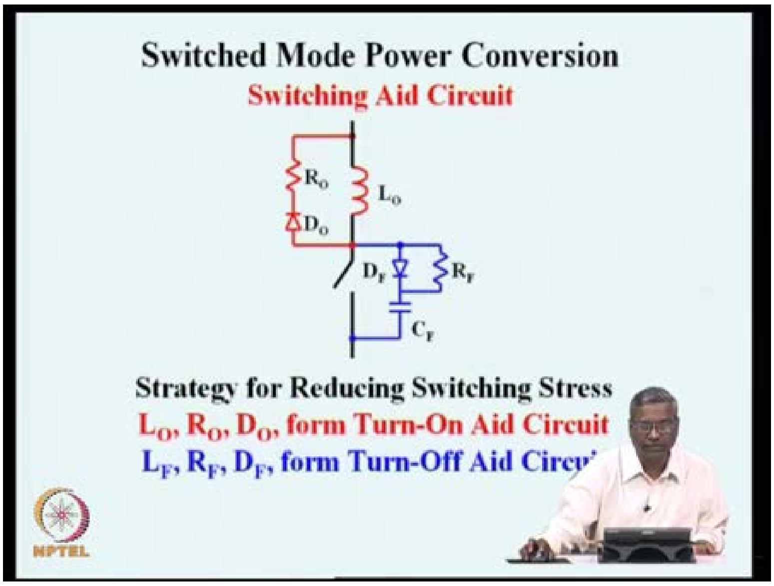

So, what you see here is a typical switching aid circuit, the switch that is used is shown here there is a red color circuit elements, which are the additional elements used to help the turn on process. And the blue color elements that you see here these elements are used to make the circuit help the turn off process, just as we were mentioning that turn off process, if the load is capacitive that is advantages, turn on process if the load is inductive it is advantages. So, what is being done here is in series with the switch an inductance is put so that whenever switch is turned on current has to rise through this inductance.

So, for a short duration the circuit behaves like an inductance, helping the process of turning on. In the same way when the device switching off a capacitor coming across the device. So, that ensure that the voltage across the device will rise slowly and that will ensure that the device turned off is like a capacitive load, the preferred of a load. The strategy for reducing this switching stress is by making the circuit behave like an inductor during turned on and capacitor during turn off, but then the flip side of this is that, this which is good for turn on will become bad for turn because if you turn off current in an inductor, you will have an l d i by d t over voltage induced.

Similarly, if you turn on this switch C will dump all its energy to be switch, and give rise to a large over current. So, to overcome that we have additional elements here, when the switch is turned on, turned off the current in the inductor will be freewheeling through this circuit. So, there is a path for this current to flow so that will ensure that the current in the inductor will not interrupted. So, there will be no over voltage because of the inductor which help the turn on process. In the same way when this device is turned on, the capacitor cannot discharge through this diode because of the opposite polarity, it will discharge through this R f. So, that that will ensure that the capacitive energy is dumped into this through a limited current, limited by this R f.

So, what we see here is a switching aid circuit L naught or helping the turn on process, c f for helping the turn off process, but the bad defects of L naught during the turn off process is over come by providing a freewheeling path for the inductor. And similarly, the bad defect of the capacitor during turn on is provided by a polarized resistor, this resistor will ensure that when the capacitance discharging into the switch, it has to do it through the R f, L naught, R naught, D naught are the on state helping circuit are turn on aid circuit L f, R f, D f or the turn off aid circuit.

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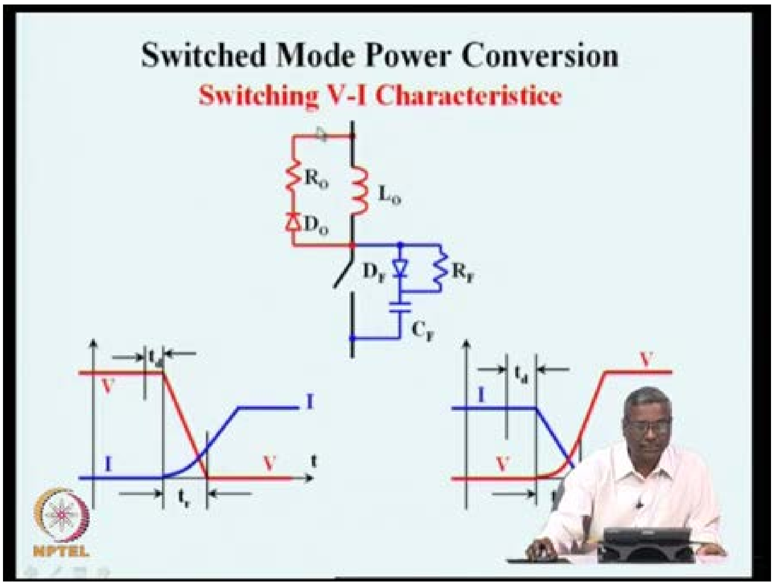

So, this kind of a additional circuit ensures that whenever, the device is turning on the current rises slowly and then reaches the full current. Similarly, when the device is turning off the current drops linearly, but the voltage rises slowly and eventually reaches the full voltage. So, this type of switching aid networks are popular whenever, you wish to reduce the switching over voltage and over current stress.

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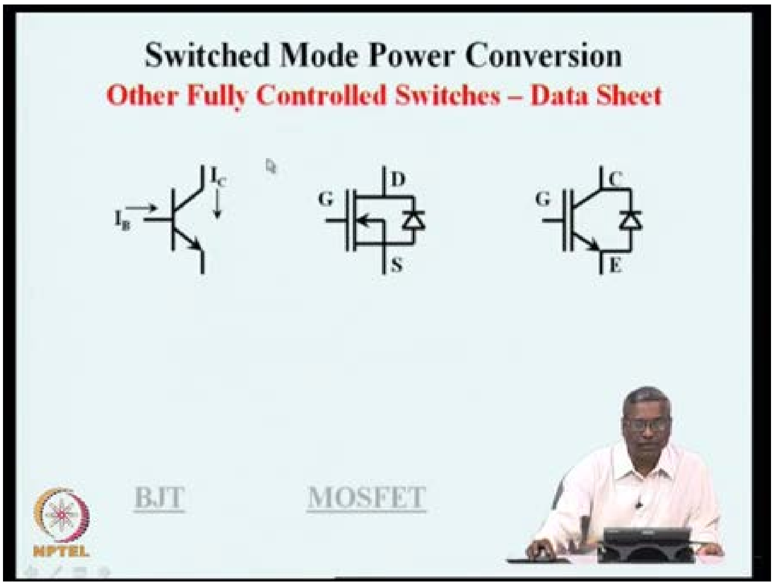

The other fully controlled switches can been seen from the data sheet. I think we have already seen this data sheets a B J T and MOSFET and an I G B T.

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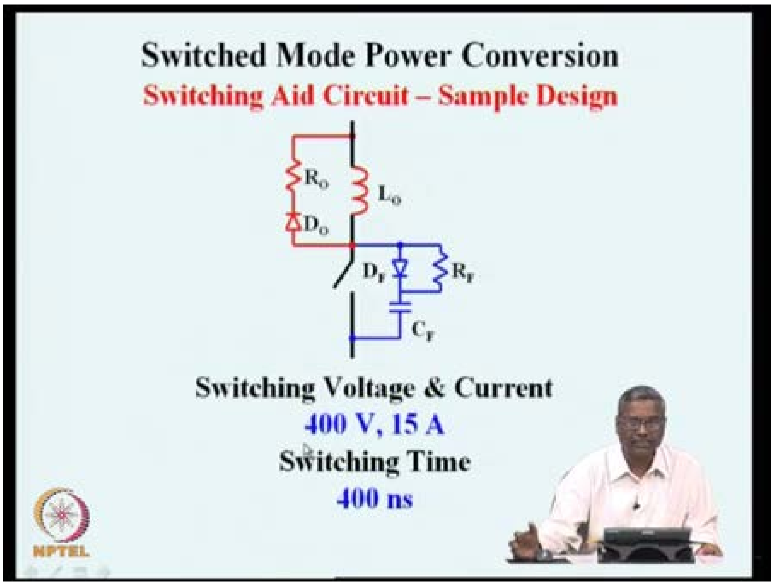

So, let us see some sample design this is a network, which is used for a switch 400 volts 15 ampere switching time is 400 nano seconds. In this case if you do not use any switching circuit, the apparent loss will be 400 volts 15 amperes, 400 nano seconds.

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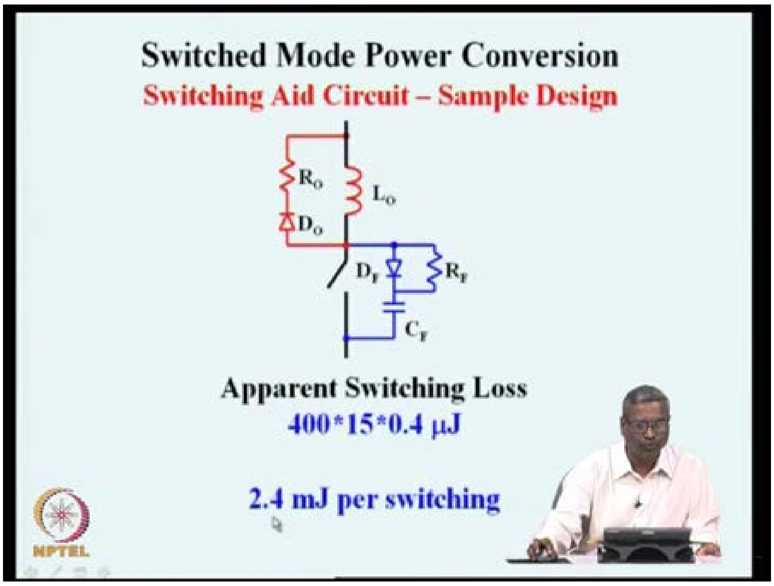

That is about 2.4 milli joule, this the apparent switching loss, full voltage and full current for a small duration of 0.4, this the order of switching loss.

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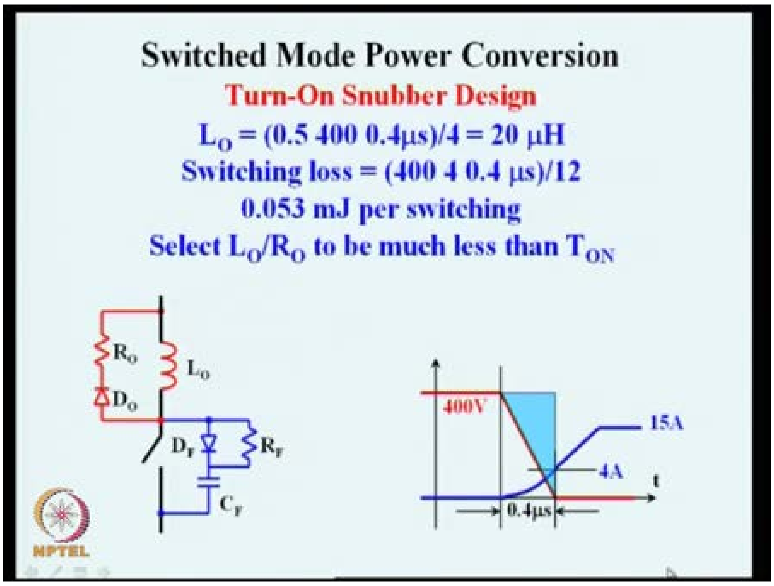

But when we use this turn on kind of a snubber, when this voltage is dropping we limit this rise in the current by providing this L naught, you can see that the additional voltage here see this a device voltage. Supply voltage is 400 the difference between supply voltage and the device voltage is this block, this a triangular block. That area is the volts second across the inductor that area divided by L will give you the rise in current, or we can put this in the other way. The required inductance is the volts second divided by the current that you want, we can keep this current about one-fourth of the total current that give rise to 20 micro Henry.

So, this L naught has to be 20 micro Henry and that will result in a switching loss which is much less instead of 2.4 mill joule, it has now dropped to 0.053 mill joule, almost 50 times less. In order to provide a suitable this suitable freewheeling path here, select this L naught, R naught time constant to be much less than the on time that is following. During the on time this should completely reset. So, L naught, R naught time constant must be much less than T on. In this way it is possible to design a similar turn off circuit, which is the blue one. Let us take the switching time for turn off to be 800 nano seconds, the apparent switching loss is about 4.8 mill joule because the time is double. Now, the loss is also double.

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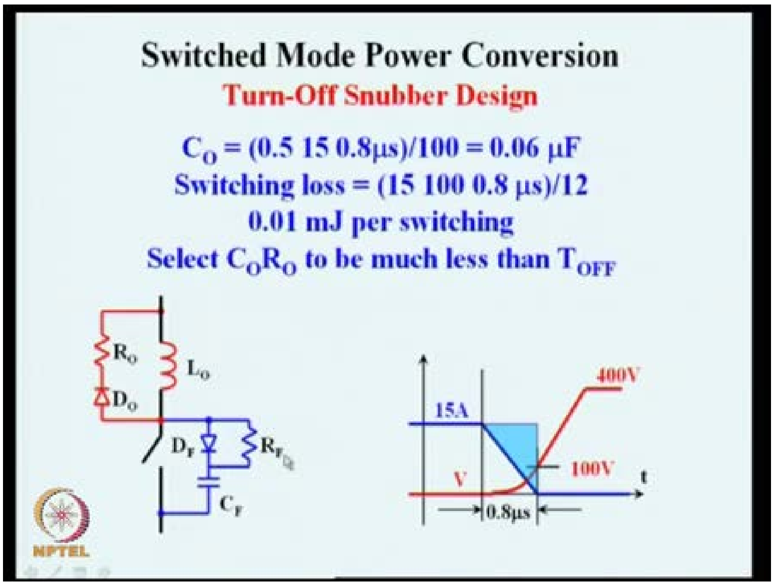

Now, we are limiting the rise in voltage by providing this capacitance here and we follow the same process, we allow this rise in voltage to be one-fourth of the total voltage. So, this triangle area that you see here is the ampere second that is the coulomb that flows into the capacitor, coulomb charge half of full height 15 into 0.8 micro second divided by rise in voltage 100 is the value of capacitance that is 06 microfarad. Switching loss as reduced almost 15 times, 50 times less the R naught, R f is to be selected now, this is not C naught, R naught this must be C f, R f this has to be much less than the half time. So, from that time constant it is possible to select this R f value.

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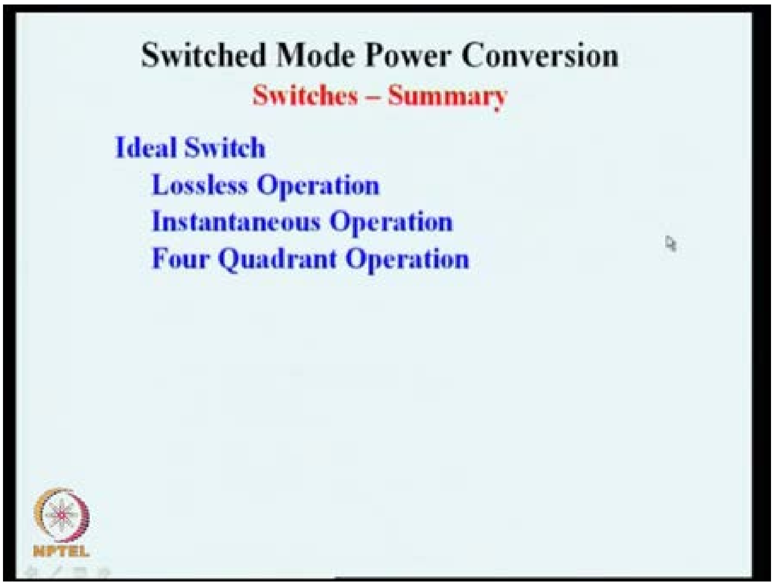

Now, probably to summarized ideal switches have lossless operation, instantaneous switching 4 quadrant operation.

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Real switches there are several of them, uncontrolled switches, semi controlled switches, controlled switches which are B J T, MOSFET, I G B T and so on. Most of these are single quadrant switches, but we can connect them in a combination to get multiquadrant operation. The most important non ideality in this which is the losses, and they have to be handled through appropriate thermal design.

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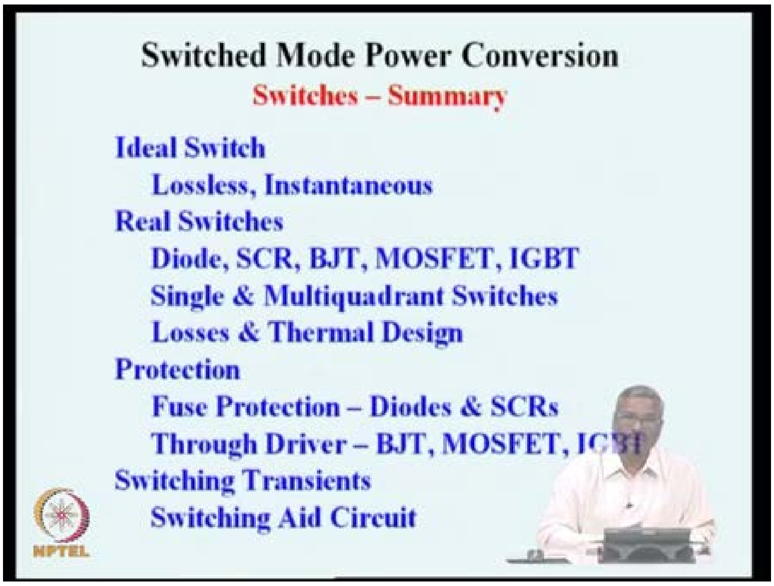

The devices require protection for diodes and S C R's protection through fuse, we find out what is the i square t tolerated by the device. And what is the i square t allowed by the fuse, if the fuse i square t is less than the device i square t then proper protection will take place, but controlled devices can be protected through the driver itself. In case you sense the over current happening because of short circuit, that is possible to switch off the device, through the control mechanism. So, that is the applicable to B J T, MOSFET, I G B T and so on.

And switching transient can give rise to voltages and currents, which are much higher than the rated voltage and current, in such a case it is necessary to design switching aid circuit which will help in maintaining the peak voltage and peak current to within safe limits. So, with this we have got some idea about switches, what are the switches, how are they featured for their ideal performance, what are the real switches and what are the features of the real switch in comparison with the ideal switch, how do you read the data sheet understand many of the performance switchers, and how do you protect these devices and so on. In one of the future lectures, we will go on to other devices inductors, transformers, capacitors and so on. And once all the components are known then we will see how to put them together for the purpose of power conversion.