Power Electronics

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Lecture - 3

In my last class, I told you what is power electronics and goal of power electronics. Now, what is the definition of power electronics? Power Electronics is the technology associated with efficient conversion and control of electric power by power semi conductor devices, that is the definition of power electronics and what is the goal of power electronics? It is to control the flow of energy from electric source to electric load. I have been telling that power electronics is very popular, it is being compared with computers, it is being said that it is an enabling technology for distributed power generation. So, if it is so popular, it has to be very efficient in the sense, power electronic equipment should have very high efficiency. It should be highly reliable. Cost, size and weight should be as low as possible. So definitely, computer power supply is so light it should be power electronic equipment.

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Fan regulator, so small compared to the conventional resistor type, definitely this is power electronic equipment. It is small, highly efficient. Cost wise, may be this is definitely higher than the conventional regulator. The conventional regulator, I was told that it cost about 60 rupees and a good regulator, a good power electronic regulator cost around 100 rupees or so. May be this equipment cost around 50% more than the conventional resistor type regulator. So, while evaluating the cost, you need to find out the payback period. This is not the initial cost; you may be able to pay more in the beginning. The question that should be asked is how fast you can recover that cost? The so called up payback period. Highly efficient, there is no power loss here or power loss is very small. That is why it is so small, is mounted inside the switchboard.

Whereas, the conventional fan regulator with a resistor type, there is power dissipation, so energy is being loss there, so definitely the total power consumed by the fan and the regulator is high. Therefore, you have to or electricity bill is high. So, you need to find out or one has to determine the payback period rather than the initial cost. So definitely, this is the power electronic equipment, whereas the regulated power supply that we are using in the lab is so bulky, so heavy. It is not a power electronic equipment. But then, both of them are doing the same thing. Regulated power supply also gives a plus or minus 5 or 12 depending upon the voltage rating. Even a computer power supply, it gives plus 5, minus 5, plus 12 and minus 12. Both of them are doing this, almost a same function. So, why it is so compact and why it is so heavy? We will see.

In other words, here there is a question, how can the circuit change the voltage level yet dissipate low power? Input to both the regulators is a single phase AC. So, why is that one circuit consumes or dissipates less power compared to the other?

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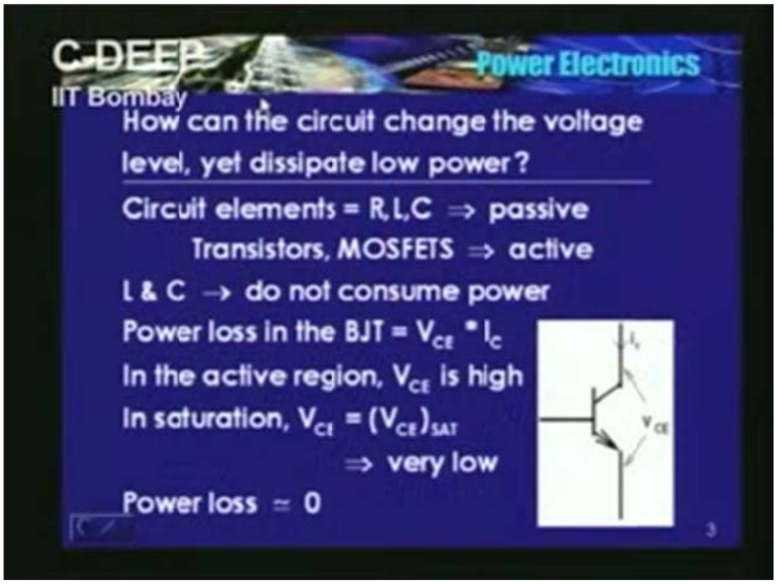

See now, all of us know the circuit elements are resistor Land C. They are conserved to be passive elements and transistors, MOSFETS, they are considered to be active. There are other active elements also, I will tell you some time later. At least, BJT or transistor or MOSFET you would have studied by now. In the passive elements, resistor consumes power whereas L and C, they do not consume power. Now, how about the active elements? See in this circuit, I have a NPN transistor. Now, what is the power loss that is taking place in the device, when it is on? It is the collector current I_C into V_{CE} is the power that is dissipated here, power loss. So, power loss in the BJT is V_{CE} into I_C and we all know that if I operate this transistor in active region, V_{CE} is high and as the, if the transistor is operated in saturation, V_{CE} is low. So, the power loss in a transistor can be reduced if I operate it in saturation.

So in that case, V_{CE} is actually V_{CE} is set, see for a small signal transistor, the teacher would have told you it is as low as point two volts. But then, this voltage increases as the current rating also increases. We will see sometime later. So, V_{CE} sat into I_C is very low. So therefore, if I operate the device in saturation or if I operate transistor in saturation, I can reduce the power that is dissipated in the transistor. So, what are the conclusions that I can make. In a power electronic equipment, I should be using or we need to use only L and C and the active devices, say for example if I am using a transistor, we should operate it in saturation. So, if I use resistor or if I use in any active element and operate it in active region, that is going to be power loss.

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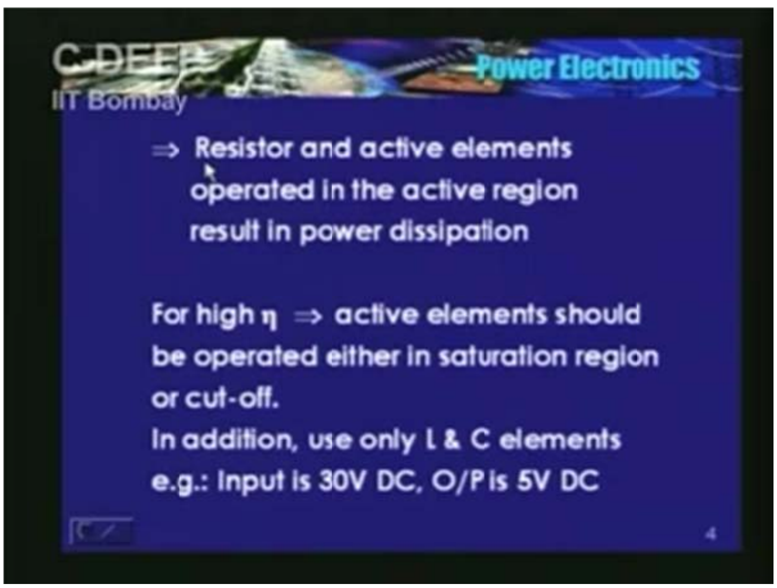

So see, here is the conclusion. Resistor and active elements, operated in the active region is the MOS or a BJT, they result in power dissipation. Therefore, we want to achieve high efficiency, active elements should be operated either in saturation or in cut off. When there is cut off there is no current, again the power loss is zero approximately. In addition, you use only L and C elements. Take for example, input is 30 volts and output voltage is five volt DC that is required. I have an input 30 volts, the circuit require five volt DC. How do I get this 5 volts? I have considered three different ways. One is what we studied in the basis circuit theory, use of potential divider. Use of potential divider and I can get the required output voltage. So the moment I use a potential divider which is nothing but a resistor, there is going to be a power loss I square R loss. See here, this is the circuit.

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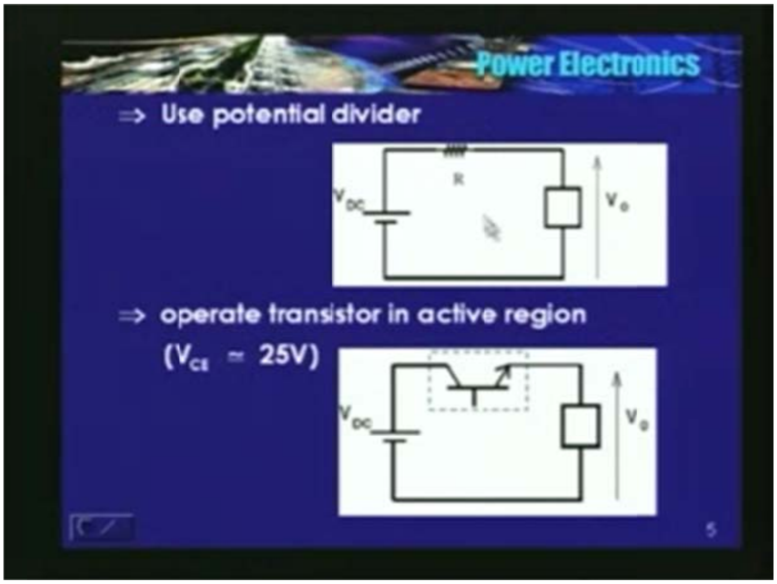

Input V_{DC}, I have connected R. You vary this R such that you get a required voltage, required output voltage. Second case is I will use a transistor, connect it in series, input is 30, output I require is 5 volts, so somehow I have to operate the transistor in such a way that voltage across it is 25 volts. This is a circuit, is something like this, input 30, output that I want is five, the remaining 25 volts should drop here, across the BJT. So, 25 into whatever the current that is flowing in the load is the power dissipated in the transistor. Now, what could be the third option?

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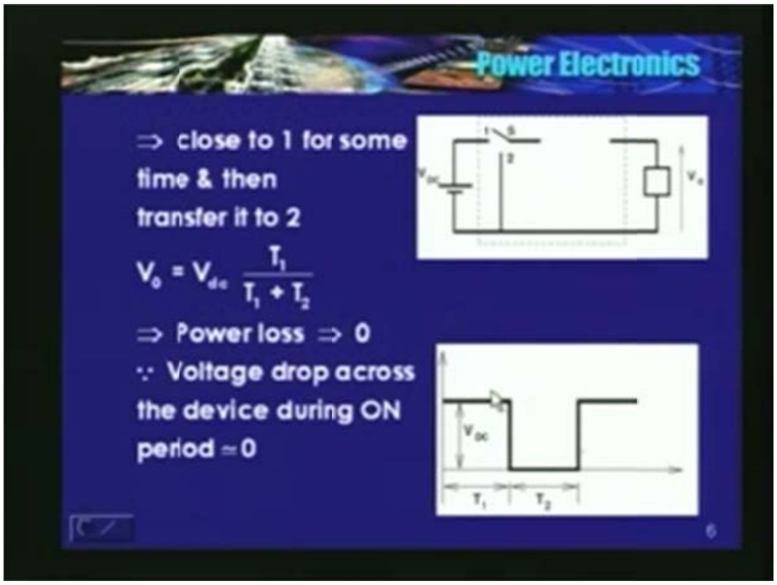

See for some time, I close the switch to position 1 and for some time, I will close the switch in position 2. As, I am not going to discuss the various parts of this circuit, that will be discussing some time later in the course. This is the voltage that is being applied when I am closing to switch 1, it is a V_{DC} and when I am closing the switch in position 2, it is zero. Now, what is the average value of this voltage? When it is 1 for T_1 seconds, it is V_{DC} the switch in position 2 for T_2 and that voltage applied is zero.

Now, the average value of this voltage is V_{DC} into T_1 divided by T_1 plus T_2. Now, depending upon V_{DC} and the required value of V_0, I will adjust T_1. Since this active device, the switch is operated in saturation, power loss across it is approximately zero, thereby increasing the efficiency. So, I am here applying or I am controlling the switch such a way that average value is controlled to a required value. So, this is the principle that is being used in the power electronic equipment. Now to summarize the application of power electronics, to be very frank, power electronic is used in almost all the equipments or wherever an efficient power conversion that is required, there is no way out.

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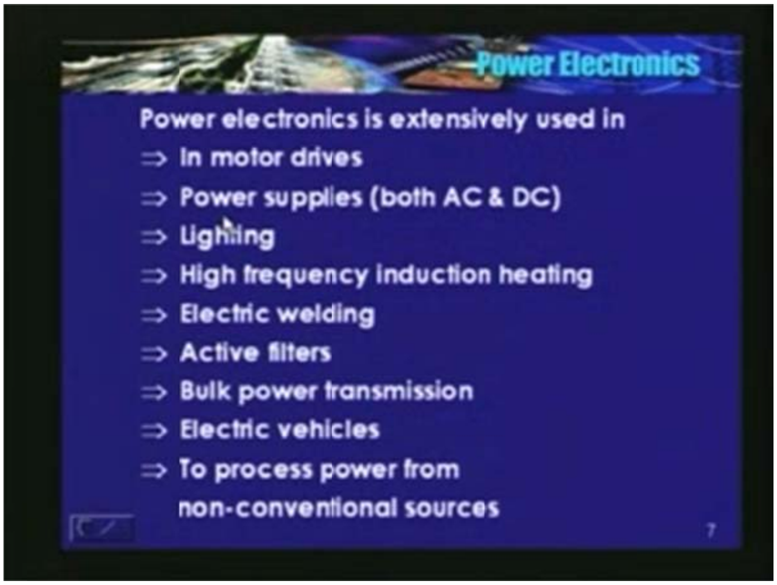

So, I just listed few applications, very few. Major application is in motor drives to control the speed or to vary the speed over a wide range because almost all the machine, separately excited DC machine, induction machine, constant speed motors, the application requires a wide variation in speed. You have to use a power electronic converter. Power supplies, a regulated or a power supply that is used in a computers, a UPS, the UPS that is used in our home, the moment AC power supply goes, there has to be or there is an equipment which provides as a AC supply again.

Lighting, especially when the input voltage is very low, the convention ballast would not work. There is a voltage range for the conventional choke or a ballast in a fluorescent lamp. If the input voltage falls below a certain value, it will not glow. Whereas, if I use an electronic ballast, it can operate it even at a very low voltage, very low input voltage. The fourth one is high frequency induction heating, electric welding, active filters. What is an active filter? In the sense, if there are harmonics in the supply, you need to filter them.

So, again you require power electronics. In transmission line, voltage support to provide reactive wars, to increase the power transmission capability, to transmit the bulk power that is some nothing like that HVDC, electric vehicles to process the power from a non conventional source. I told you that, power electronics is an enabling technology for distributed generation or without power electronics to be extremely difficult to generate power from non conventional sources. These are a very few applications.

Now, what is a reason for the progress in power electronics? The progress in power electronics is primarily due to the advances in power semi conductor devices. I will just show you some of them, a small diode, point five amperes. It can carry the rating is point five amperes it can block a 50 volts or so.

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High power diode can carry 40 amperes and it can withstand 1200 volts. See, if I use a diode in an AC supply in the negative half cycle, diode may get reverse biased or get reverse biased and it has to block or withstand a voltage, whatever the input voltage. So, this diode can block a voltage up to 1200 volts.

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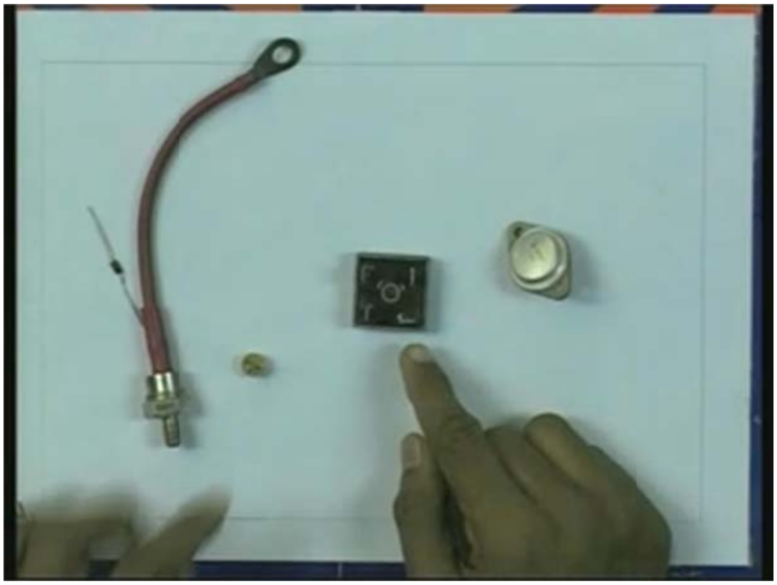

A small BJT, a transistor NPN, SL100, can carry rating is 500 milli amperes and can be used in a circuit or it can block up to 50 volts or it can block up to 50 volts. See the power transistor, this was mounted in the rear side of the power supply, regulated power supply, yesterday I showed you. A single phase diode bridge, see here, there are single phase diode bridge is nothing but this. This is a single phase diode bridge, four diodes.

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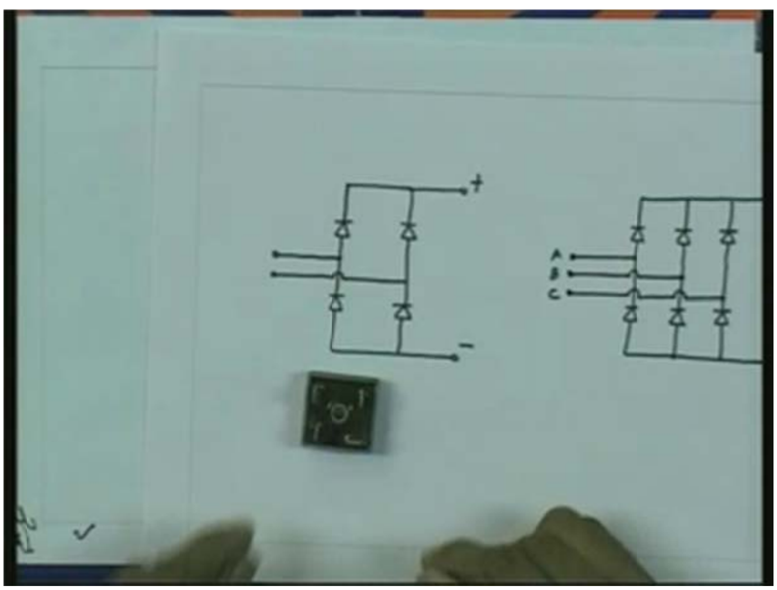

Input, I need to connect, these are the two terminals and these are the two plus and minus, one of them could be plus and minus, this is the two inputs, a single phase diode bridge. A small transistor, 500 milli amperes, 50 volts, very common may be as used in the lab.

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One module, see here there are two such devices, a switch which can be controlled using a gate signal or a base drive if it is a BJT, this switch and a diode that is connected across it. Why it is? We will see later.

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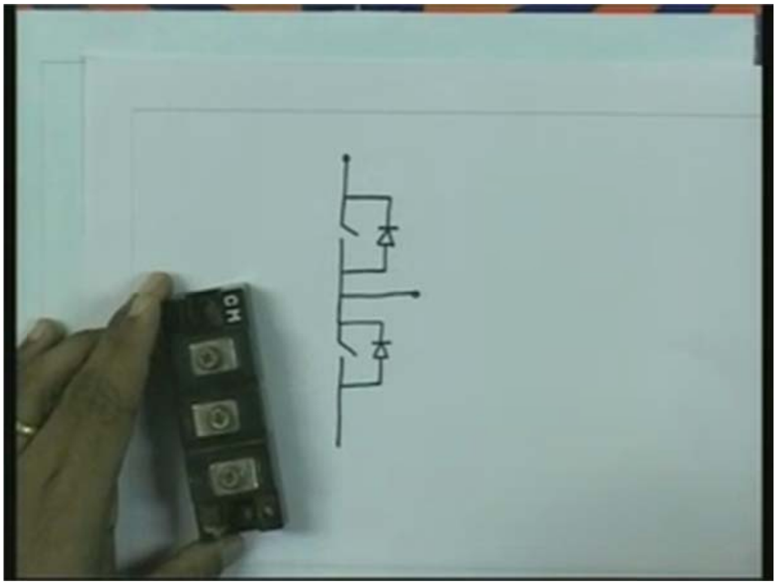

So there are inside, we have two such devices and two diodes, anti parallel diodes. Each device can carry 50 amperes and it can block as high as 1200 volts. See these three terminals, 1, 2 and 3 corresponds to these 3. See, there are two terminals here. The control signal, the base drive is to be connected between these two. Similarly, for this switch these are the two terminals. This is one. Now see, there are dedicated chips to supply the required base drive to this transistor. You do not have to use a separate discrete component to feed or to supply the gate drive for this device. Here is a dedicated chip. All the components are inside dedicated chip. There are various pins have been brought out and it can be directly fed or outputs can be directly connected to this two pins and you can operator one such device. To operate both of them, you require two such dedicated chips.

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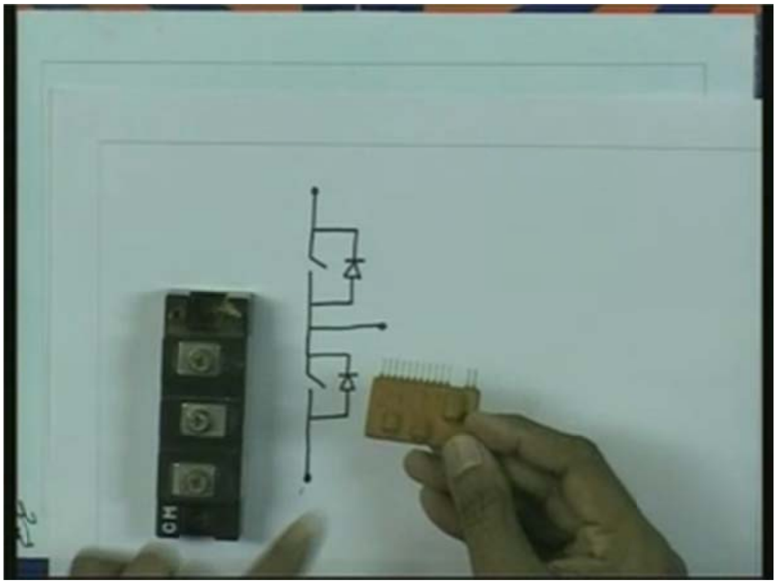

See another, a very recent power module, what it is? See here, there are three such legs if I consider this is one leg, there are three such legs here. Each device can carry again 75 amperes and it can block 1200 volts. The rating there are 6 such devices integrated

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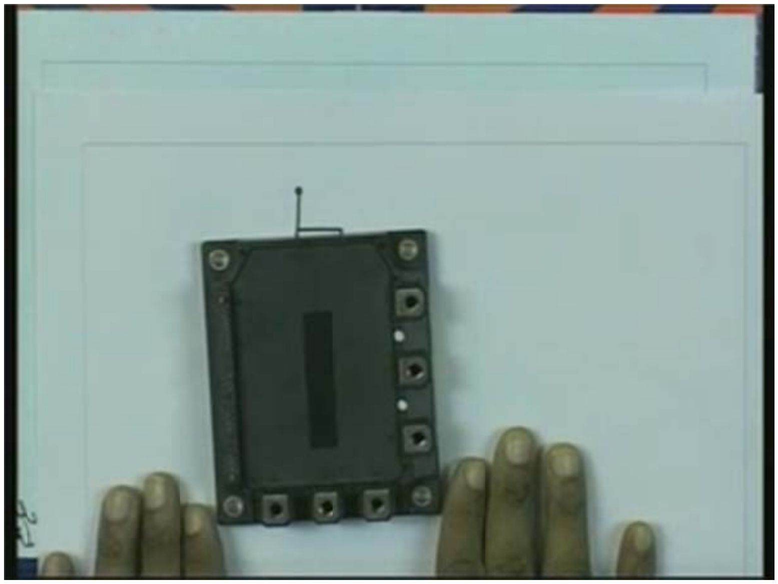

I said, you require a separate dedicated supply or you need to have a separate driver circuit to supply the required gate drive for this transistor. So, this is the dedicated chip that is used to drive this. You can design your own circuit using various discrete components, transistors that are small resistors and op-amps. Whereas, this circuit has built in the driver circuit what is known as the intelligent power modules. The protection part is also integrated here. Protection in the sense, in case current is higher than the required or higher than the rated value, automatically the gate drive is blocked, intelligent power modules, the protection is built in.

Whereas here, if you are driving, if you are designing every circuit one has to design your own protection circuit, to protect this device, whereas the protection is built in here. A small 500 milli amperes transistor, 75 in between another power transistor that used in a regulator power supply, one such leg where in there are two controllable switches, two diodes each of 75 amperes, 1200 volts. See the size, see the reduction in size, here we have to use my own external driver circuit and the protection circuit, all six such devices, protection is built in here.

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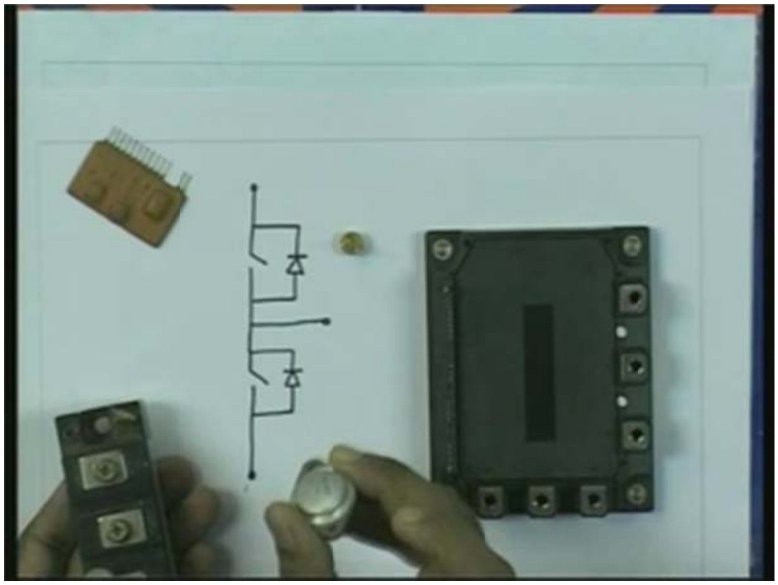

See, there is another very high power device again a controllable device. Can carry 300 amperes of current, can block again 1200 volts, two sides. Now, it requires two heat sinks, some sort of a sand witch type. Again you require one more heat sink on top of it.

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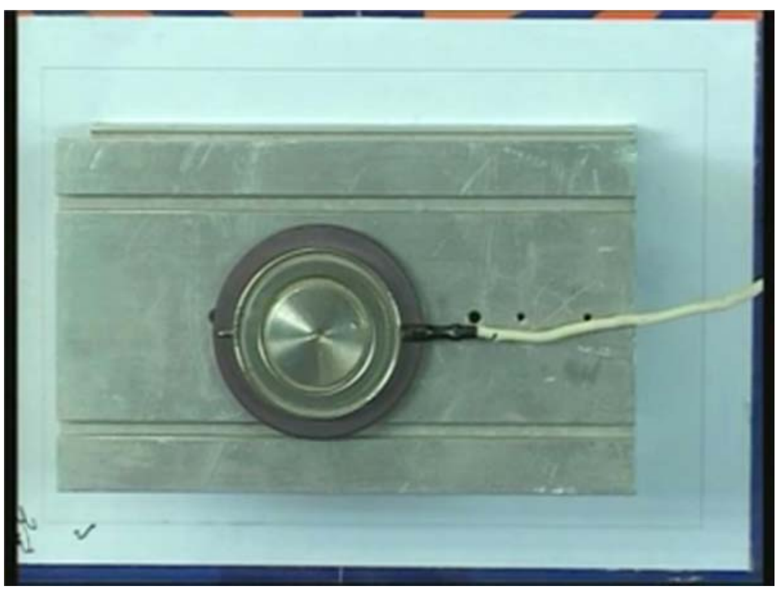

So, now you can see the progress in a power semi conductor technology. A small transistor relatively higher, two 75 ampere devices, six 75 amperes devices, there are six diodes, anti parallel diodes. Here there are two anti parallel diodes, 300 ampere device, dedicated IC, a dedicated circuit which provides the gate drive for the controllable switch. So, the power electronics, the progressive power electronics is primarily due to the advances in power semi conductor devices.

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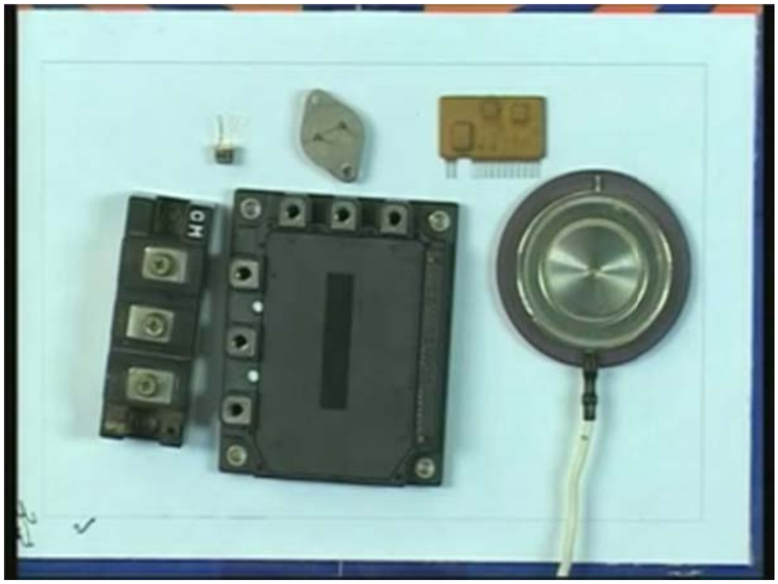

Apart from the power semi conductor devices, it is a fast processor like digital DSP, digital signal processors, dedicated chips, various circuit configurations, what exactly are the various circuit configurations, I will discuss in the course. Then they can have various control and estimation techniques and materials. I will just give another example. See here, how smaller a current sensor works similar to a current transformer. The rating is 50 ampere turns, in the sense I have put only one turn here. So, I can supply as much as 50 amperes of current through this.

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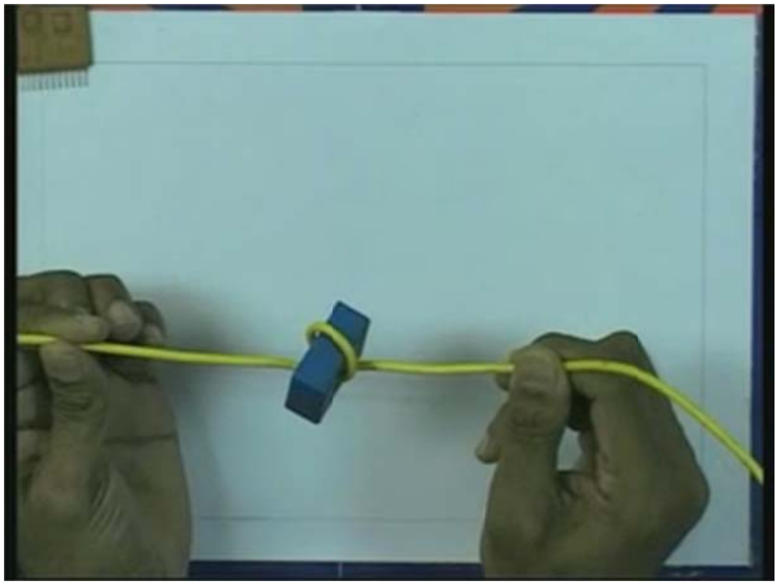

What do I need to do? There are 3 pins plus 15 volts, minus 15 volts and a small resistor but is similar to a CT burden. See, how compact it is, fifty ampere turns. Total ampere turns required, plus 15, minus 15 and a small resistor what is known as equivalent to a burden. Excellent linear characteristics, very good response, band width is 0 to 200 kilo hertz, a current sensor. So all this factors are responsible for progress in power electronics. Again let me tell you one thing, I will show all this power semi conductor modules at the appropriate time, during the course. Now, what are the significant events in the past history of power electronic? See, I will show.

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In 1783, the concept of semi conductor came by VOLTA. In 1830, rectification effect of copper oxide was identified or observed. 1876 selenium rectifier, 1896 the single phase bridge rectifier circuit and 1897, it is three phase bridge rectifier circuit. I will just show you what is single phase bridge rectifier and a three phase bridge rectifier, it is simple. See here, a single phase bridge rectifier. Something like this, a single phase bridge rectifier, diode rectifier.

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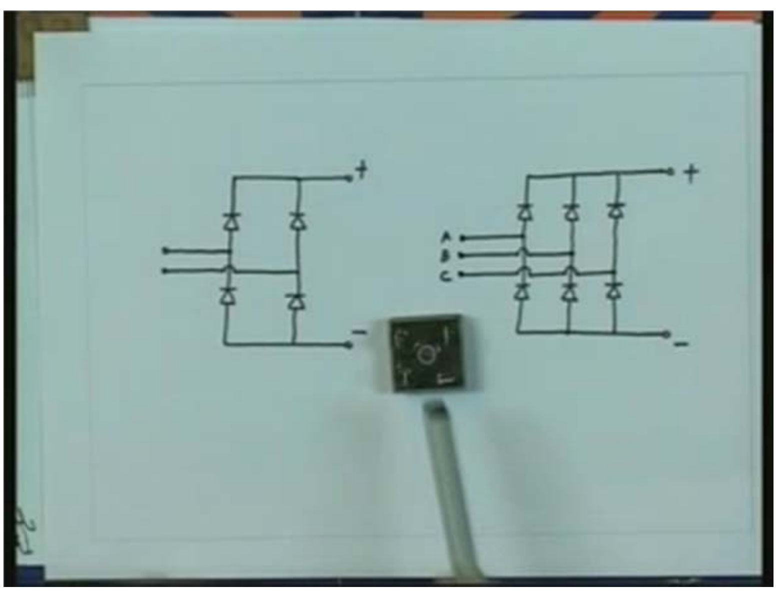

Single phase, phase in neutral, here a three phase, three such legs. See, the beauty of this circuit was invented in 1897, it is almost 100 years and still it is very popular. It is more than 100 years this circuit was invented and still it is being used extensively and in 1901 an invention of glass bulb mercury arc rectifier and next major event was in 1948, invention of transistor. This is a major step, a major invention in the history of power electronics. In 1953, germanium power diode was and invented and in 1954, silicon power diode and in 1957 SCR, a silicon controlled rectifier, in 1985 it was invented. So, in 1957 SCR was invented, it could block around 500 volts and today SCR which can block a voltage of six point five KV. What is exactly SCR, the characteristics, I will tell you. So, the invention of SCR, it gave a major thrust in power electronics. So, that is about the significance events in the history of power electronics and that completes my lecture on, introductive lecture on power electronics.

Now, we will go to power semi conductor devices. What are the devices that are being used in power electronic circuits? Power semi conducted devices, it is said that they are heart and soul of modern power electronic equipment. Power semi conductor devices are heart and soul of modern powers electronic equipments. These are used as switches. All of us know, what exact is a switch? So, what are the ideal properties of the switch?

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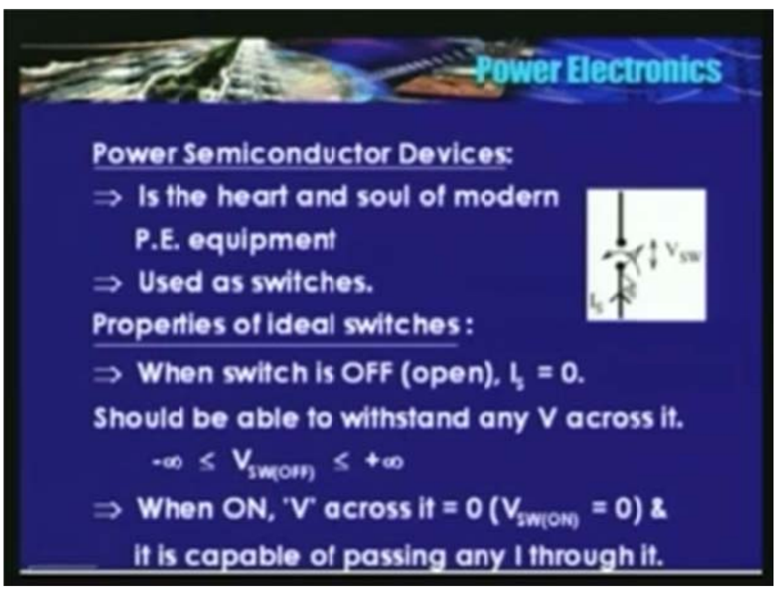

See, here is the circuit, a single line diagram and if this arrow shows that to close the switch, I need to change in this way. So, what are the properties of this switch? When the switch is off, I_S should be zero. There should not be any current flowing through the switch, when it is open and it should be able to with stand any voltage across it. In other words, this switch should be able to with stand any voltage varying from minus infinity to plus infinity and when it is on, what should happen? The voltage across it should be zero and it is capable of passing any current through it. So when it is open, zero current, any voltage and when it is closed, zero voltage, any current. So, what happens now?

The power that is dissipated in the switch when it is on or off, it is zero because when it is off, current through it is zero. So, power dissipated is zero and when it is on the voltage across it is zero. It can pass any current, so power dissipated is zero. Therefore, when the switch is conducting or it is blocking, in other words it is open, the conduction loss and the blocking loss should be zero. They will be zero. These are the characteristics of an ideal switch. What about the other characteristics of the ideal switch? Switch should be turned on or off instantaneously. See here, in the circuit I will just explain to you. I have a load, some voltage here and I have to control the voltage applied to the load. So, I should be able to close the switch instantaneously or open the switch instantaneously.

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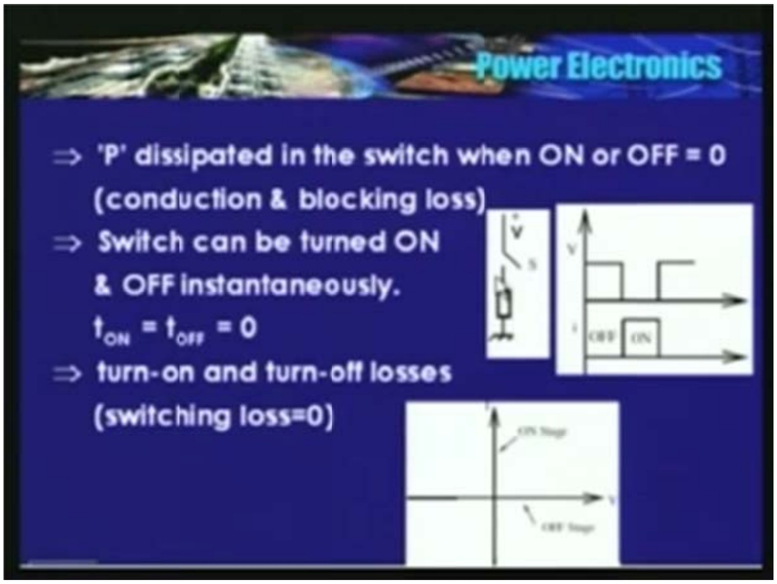

So, what is the transition when I close the switch? Voltage across it is zero and when I open the switch, whatever the voltage that is being applied here will appear. So, this transition should be instantaneous. Similarly, when it is open, current is zero. So in this period and at this point, it is turned on. This current depending upon the load transition, from zero to this current should be instantaneous. So, what is the consequence? If the changeover is instantaneous, time taken or t_{ON} that is equal to t_{OFF}? Both are zero. So therefore, the loss that is taking place during on time and when it is being turned off, it is zero. I will repeat, the transition from off state to on state is instantaneous. Therefore the turn on loss is zero.

Similarly, from on state to off state again it is instantaneous. The loss again during turn off process is zero. So, these are nothing but the switching losses, the losses that are taking place during switching, they are zero. So, the ideal switch should have zero conduction losses, zero blocking losses and zero switching losses. So, if I plot the device characteristics in XY plane, in VI plane sorry. Off state, any voltage, it should be able to block any voltage, plus infinity to minus infinity and when it is on it should be able to carry any current. This is how it looks.

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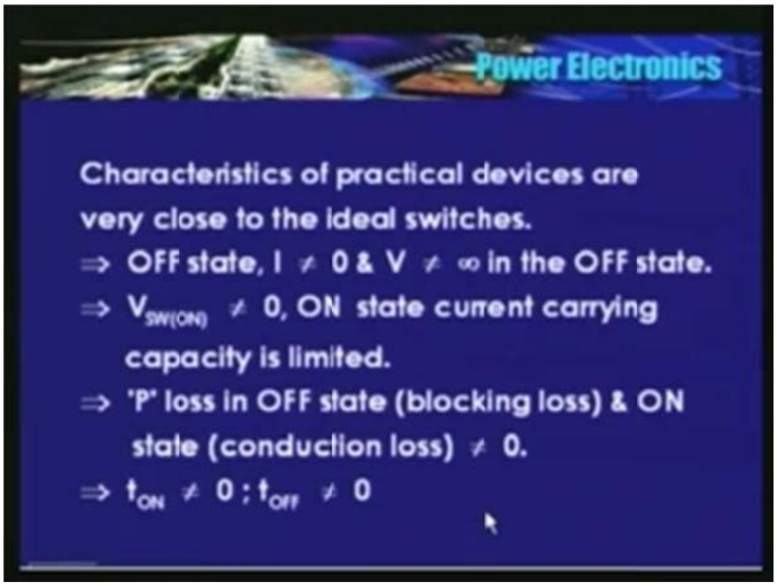

How about the practical devices? Can you have these ideal characteristics in practice? Answer is no. It is rather impossible to get these ideal characteristics but then there should not be a much difference between the ideal characteristics and a non ideal characteristic or an ideal switch and a non ideal switch. See, efficiency of an ideal transformer is 100%, there are no losses at all but then efficiency of a good transformer is of the order of say, 98% or so. So you cannot have a long difference between an ideal switch and a non ideal switch.

So, in a non ideal switch, off state when the switch is open, current is non zero, very small current flows. What it is? We will see. When it is off, it cannot block any voltage. That is, its voltage rating. You cannot exceed that voltage. For example, any switch that is used to control the incandescent bulb or a circuit breaker, a miniature circuit breaker MCB that is used in our home at the at the main switch, each of them have a voltage rating.

Similarly, a semi conductor switch, it has a voltage rating above which it will fail also when the switch is on. Voltage across it is non zero and again there is a maximum current carrying capability. It cannot exceed. So, off state current is non zero, there is going to be losses, when the device is blocking or when device is off. When the device is on, voltage across it is non zero. There will be a conduction loss. Therefore, both blocking as well as conduction losses are finite. Again transition from on state to off state is not going to be instantaneous.

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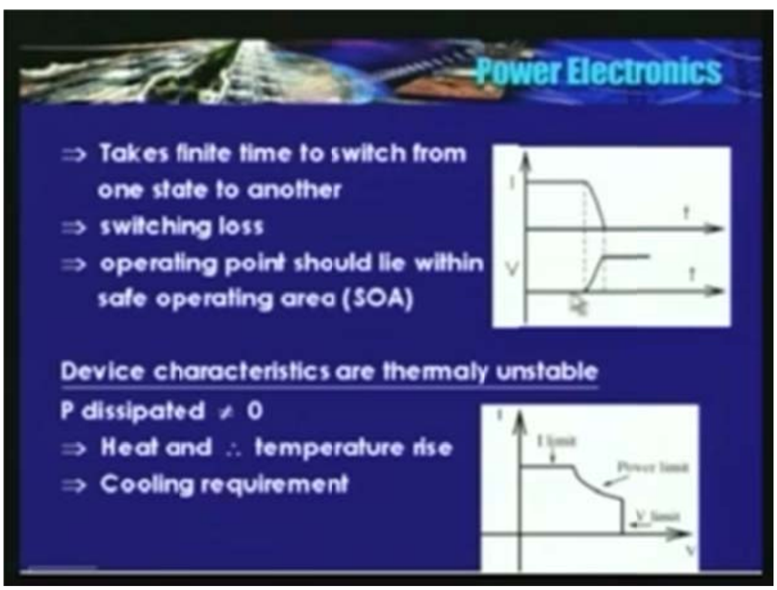

See here, current could follow this path. Current slowly falls and this is the voltage across the device or the switch is not instantaneous. So, that is going to be finite losses during switching. Therefore, the locus in the VI plane is not going to be along the X axis and along the Y axis. There are limits. I showed you, there are six devices here or three such legs, each of 75 ampere and 1200 volts it can block.

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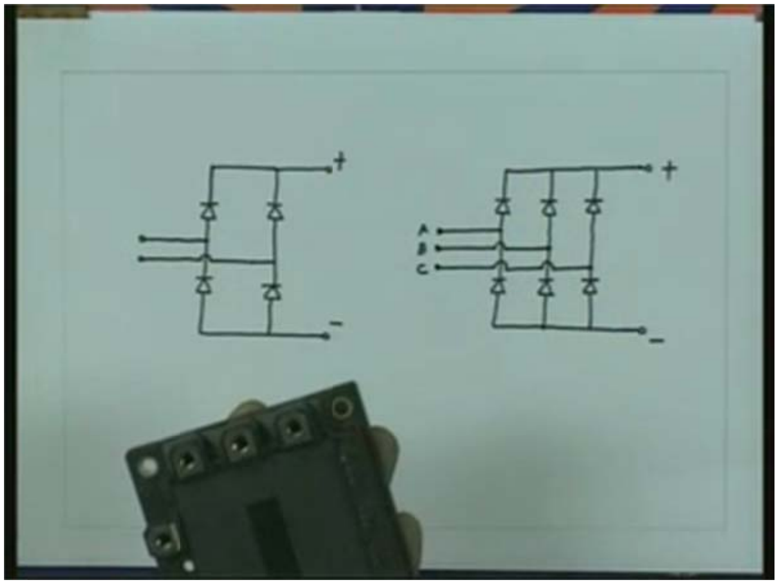

But then, each device at any given time will not be able to carry 75 amperes and voltage across it is 1200 volts, no. There is something known as the maximum power that it can dissipate. That is all the devices are or in other words, all the devices are thermally unstable because at any given time, power loss that is taking place is voltage across it into the current that is flowing through it. Because, as the power loss increases in the device, the junction temperature will increase and if it exceeds a certain value, it will fail; what is known as the thermal limit or the power limit.

So, each device has something known as the safe operating area. At any given time, the operating point should lie within the safe operating area, SOA zone. One such area is shown here, I limit; maximum current it can carry till as voltage range. See, you cannot pass 75 amperes at 1200 volts, it just not possible. So there is a limit, I limit till a certain range. So, this is a voltage, the voltage across it could be 1200 volts but then current should be within this limit. See, this is a limit and this is the power limit. I have just shown here voltage limit, I limit and the power limit. There could be other zones also.

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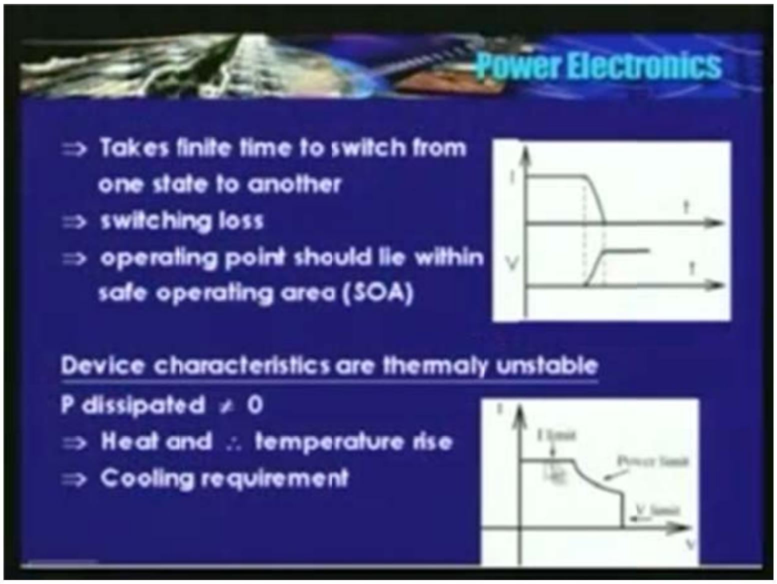

So, depending upon, we will be discussing various devices and for the each device we will discuss the safe operating area. So, I told you that each device is thermally unstable because power dissipated is non zero during conduction period, during switching and also during blocking mode. Therefore, power dissipated is non zero, there is going to be a temperature rise, so heat has to be dissipated. So, we need to know or one has to calculate the heat sink requirement or the cooling requirement. There are various types of heat sinks and may be, if you observe in the power supply that I have showed in the computer, there is a small fan inside to dissipate or to maintain the temperature within the limits. So, it all depends on, the cooling requirement depends on the losses that are taking place.

That is about the characteristics of the ideal switch and a non ideal switch. Now, what are the various types of switches that are used in power electronics? One is the uncontrolled switch. Why it is known as uncontrolled switch? It is known as uncontrolled switch, because on and off is determined by the circuit in which the device is connected. I will repeat, the on and off is determined by the state of the circuit in which the device is connected. I will give you an example. See here, an uncontrolled switch. A diode is an uncontrolled switch.

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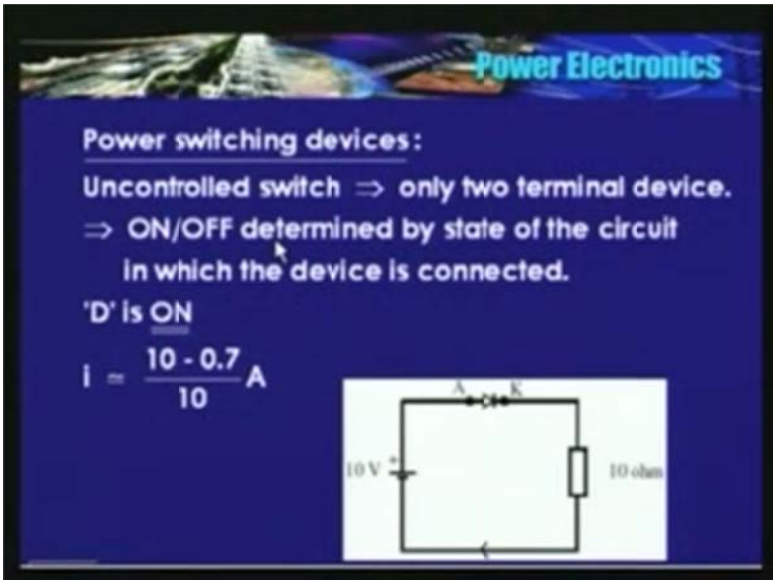

Why it is uncontrolled? Take this circuit, a ten volts DC power supply, I have connected a diode and a ten ohm resistor. What is the current that is flowing? Assuming that voltage across the diode is around 0.7 volts, the current is approximately 10 minus the drop across it divided by the load resistance approximately. I am neglecting the on state resistance of a diode, I am just saying, this drop remains constant.

Now, instead of having a DC supply if I had an AC power source, what would have happened? At the positive zero crossing, this diode would have started conducting. For time being, I am neglecting the voltage across the diode. So, if I had an AC here and the resistive load at the positive zero crossing, diode starts conducting and at the negative zero crossing, diode turns off. Therefore, the on and off of this diode is determined by this circuit here and not I cannot, you cannot determine externally or you cannot decide externally, as to when this diode should turn on or when this diode should turn off. The circuit decides, that is why it is known as an uncontrolled switch. It has only two elements, two terminal device, anode and cathode.

What is another type of switch? It is a semi controlled switch. Why it is semi controlled switch? It is because switch may be turned to one of its state, I am telling, a switch may be turned to one of its state using a control terminal and other state is reachable through the circuit only.

See, in the previous circuit, diode; both the circuits, on as well as off is completely determined by the circuit itself. But in the case of a semi controlled switch, again it is a three terminal device. SCR could be one of the examples here. See here, what is exactly SCR, I will tell you later.

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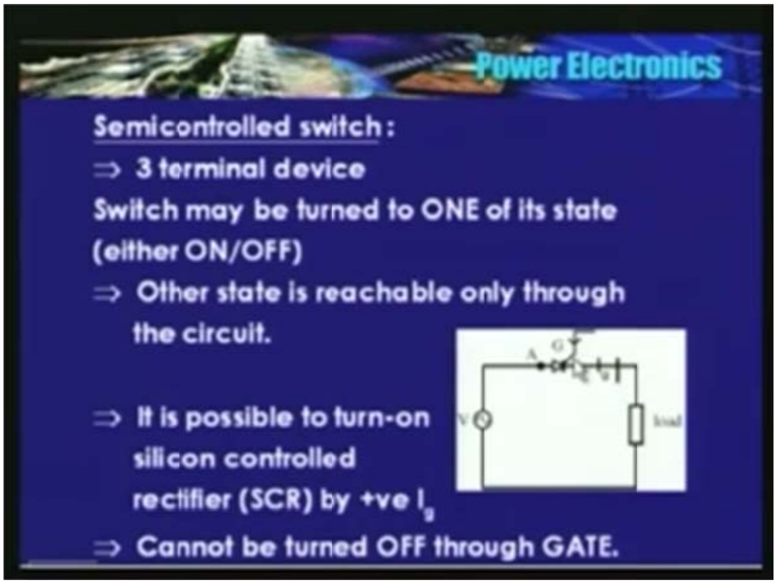

You can turn on this device by supplying a positive gate current when the device is forward biased. When the device is forward biased and supplying some gate current, you can turn this device on. Having turned on the device, you cannot turn into off using gate. See I will repeat, when the device is forward biased by supplying a positive gate current, thyristor or SCR can be turned on. But then, having turned on the device, you cannot turn it off using the gate. Hence the name, semi controlled switch.

What about the third type? So, there is a totally uncontrolled, a semi controlled, the third is a fully controlled switch. It is very obvious, both on and off should be possible using the control terminal. So, take for example, a BJT. I can turn it on by supplying a positive base current and I can turn it off by making the base current zero. So, diode is an uncontrolled element, uncontrolled switch because whether it is on or off, it is completely decided by the circuit.

SCR is a three element device, it can be turned on only by supplying a positive gate current and it should be forward biased, you cannot turn it off using gate and the third one, what is known as a fully controlled switch, a controlled switch wherein the device can be turned on or off by using a controlled terminal. Some more about it, we will study in our next class.

Thank you.