Power Electronics with Wide Bandgap Devices

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Lecture-18
HEAT SINK

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Welcome to the course on power electronics with wideband gap devices. In the last lecture, I have discussed about the PCB and parasitics related to devices and PCBs and different types of PCBs. So today I am going to discuss about the thermal related issue. So there are actually two different parameters which affects the switching operation that is one is the electrical parameter another is the thermal parameter. So thermal parameter which generally we consider as heat which is generated due to the losses in the converter either due to switching operation or It can come from the parasitics. Okay.

So now parasitic can come either from the switches or from PCB layout. Okay. So let's see how these thermal parameters are going to affect the converter operation or how to mitigate them. So you can see here.

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Thermal Design in Power Electronic Systems

- The thermal aspect in the design of a power electronic system is one of the determining factors for a reliable, prolonged, and efficient operation of the system:
  - High thermal stress can negatively impact the lifetime of components.
  - Critical thermal-stressing parameters include junction temperature swing, maximum junction temperature, and pulse length.
  - The number of cycles to failure of a power module can be expressed as a function of these parameters.

So thermal design in power electronic system basically if we have to consider, so then there are actually different factor we need to know about. So how these thermal factors are coming. So thermal aspect in the design of power electronic system is one of the determining factor for a reliable, prolonged and efficient operation of the system. Because if the temperature increases then it is going to affect the characteristics of the switches which is present in the converter So that is why it is important to maintain the temperature in the converter And to maintain the converter first we need to have knowledge about how this temperature is actually arising in the circuit Then the second part will be how to mitigate them So the thermal stress can negatively impact the lifetime of the component. Obviously, this will affect the reliability of the entire system.

The critical thermal stressing parameters include junction temperature swing, maximum junction temperature and pulse length. Okay, the number of cycles to failure of a power module can be expressed as a function of this parameter. So, this cycle to failure, it gives us like how many cycles the converter is going to operate and what will be the rate of the failure. So, based on that we can actually calculate tell about the reliability of the system so now this depends on three factors one is the temperature swing so what will be the temperature variation in the converter so let's say the device which is there in the converter that is actually turning on and turning off So during that time the temperature will also be variable So during turn on time current will be in rated condition and during the turn off time the voltage will be in the rated condition So based on that The power losses will happen So then based on the power loss this temperature will change So that will give us temperature swing Now another factor is the maximum junction temperature Now this temperature swing is going to affect the junction temperature of the device And another component is the pulse length So how long this pulse will be present Means it depends on the turn on time of the device Again this turnoff time. is also going to be variable.

Means, depending upon the load condition or the input condition, this duty cycle will be variable. Based on that, this pulse length will be variable. So, as you can see, this cycle to failure, it depends on three different factors. And these three different factors are related to the temperature. If pulse length is more, then the temperature is going to be more in the converter.

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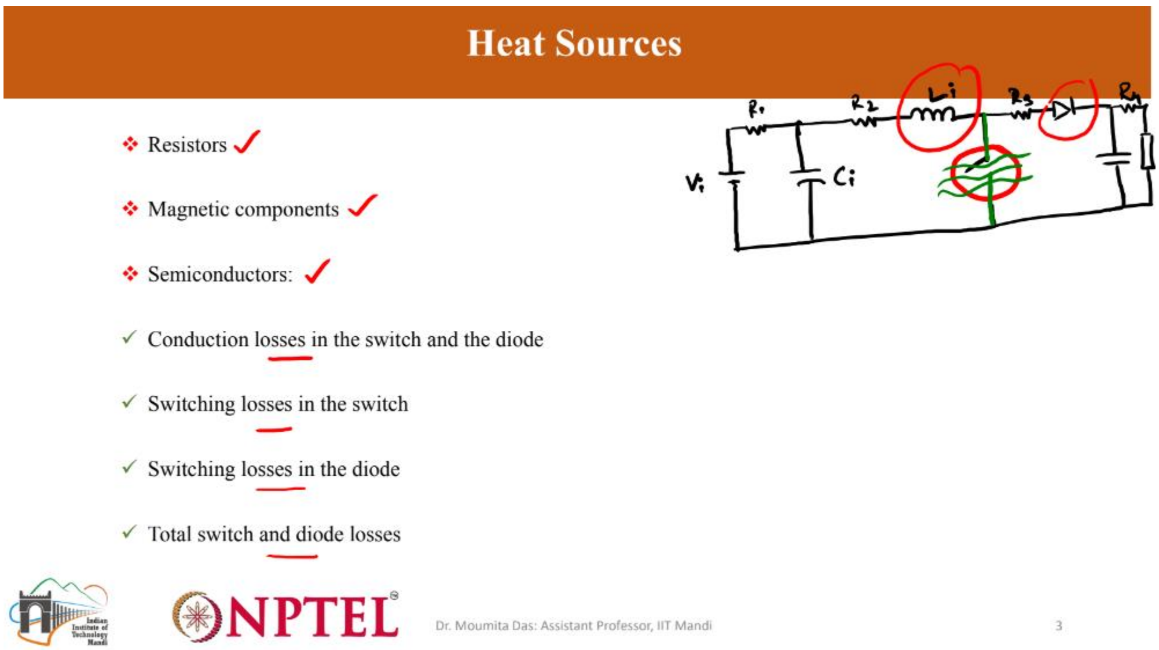

Because you know, the device will be operating for long time. So, then you can see that different factors which affects during this condition. So, three different factors you know. So, how these three different factors are coming? So, these are coming from mainly three different components. First is the resistor, second is the magnetic component, third is the semiconductor or the power switches.

Now when I say register, register it is not which you are connecting in the circuit It is something which is present in the circuit as the parasitic component So it can come from the PCB track or the device lead Or the wire which is connected during interconnection So this will give the resistor So basically if you have any converter So whenever let's say you are connecting a converter So let's say there is a DC to DC converter After input generally what happens? There is an input capacitor is present So, in between this input voltage and the capacitor also there will be some resistance. So, wherever there will be some connection, some layout. So, that will give some parasitic inductance also some parasitic resistance. So, these resistances we cannot removed from the converter. So, this will be present as the parasitic resistance.

So, this is the input inductor of the boost converter. So, then there will be some resistance along with it and again some resistance will be there with the boost converter whenever The diode is connected to it Again the capacitor will be there And then load whatever it is Doesn't matter So again there will be some resistances So these different resistances you can see R1, R2, R3, R4 So this will be there in each path I am just showing on the top path Which will also be there at the bottom path In each branch these different parasitic resistances will be present And this will cause loss in the different section of the converter. And these losses adding together will give the temperature rise in the converter. Okay, so the first component is resistor. And the second component is the magnetic component.

The magnetic component is not the parasitic inductance. Parasitic inductance is different. The magnetic component is the resistor. inductance or the transformer which is present in the converter. Okay, the main inductor or the main transformer.

Now, when I say main inductor and main transformer, ideally we consider they are operating absolutely fine. Okay, these magnetics are having two different losses. This you already you know that is known as core loss and the copper loss. These are inherent so like this you cannot control or you are not adding anything to remove this kind of losses So this will be there associated with the magnetic component So the core and the copper losses of the magnetics will also be present and that will also cause increase in the heat So now the third component is semiconductor. The semiconductor which you know as the switches or diodes.

right so this is simple boost converter it has one switch one diode if it is inverter so conventional inverter where six different switches are there so for forward operation six different switches will come into picture if there is reverse operation then the body diode also will come into picture so you have to consider all the components for power loss calculation so it will have different losses which are conduction losses switching losses in the switch and if diodes are there or the body diodes then the switching losses in the diode and total switch and diode losses will give the total losses in the semiconductor devices again that will give us idea about the heat generation in the device itself Generally in the data sheet they mention how much temperature device can tolerate. From the power loss we can comment on the temperature actual temperature which will be there due to the losses in the devices and which we can allow so that the difference we have to take care in the means of heat sink or some other method where this temperature can be taken out. So, that I will discuss in details. So, now at least you can understand what are the components which is going to affect in the heat generation of any converter and this heat generation is going to impact on the reliability.

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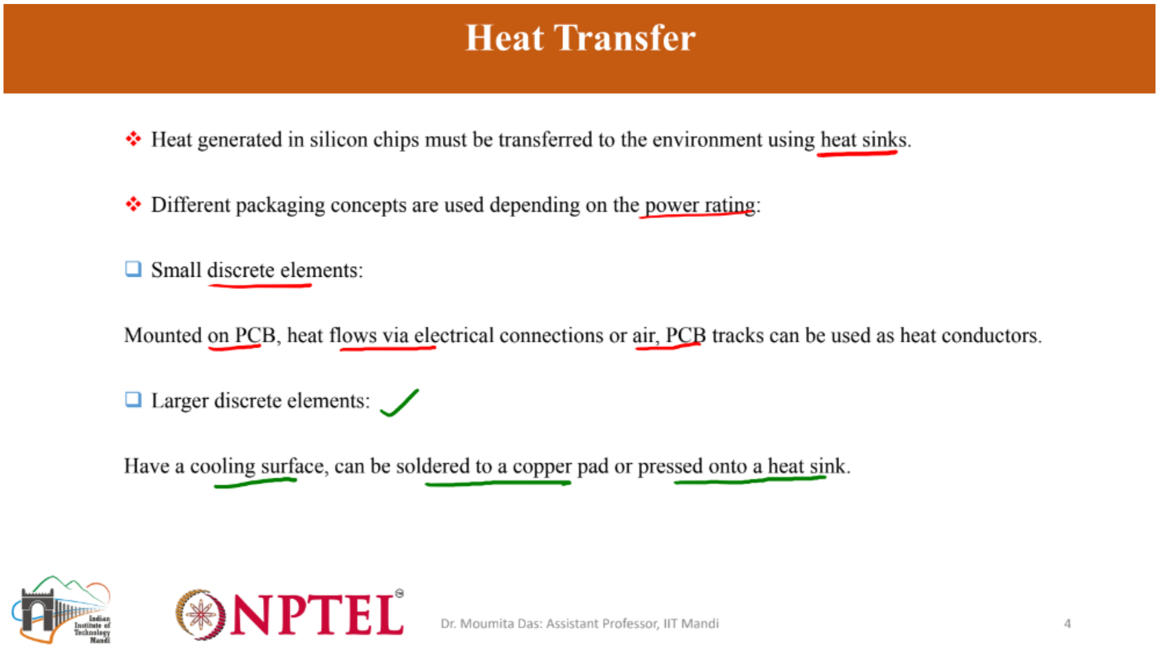

now you can see if this heat is generated in the converter due to different parameter present in the converter either parasitics or the actual so then we need to find a way to transfer the heat so as I told you so if some temperature is specified in the data sheet we always have to make sure the device is operating within that temperature range.

Okay, so then if the temperature is more we have to find a way to transfer the heat to make sure the device is operating in the suitable temperature range or the given temperature range. Okay, the heat generated in silicon chips that must be transferred to the environment using heat sinks. So generally you have seen with any silicon devices there will be heat sink connected Same applicable for power module as well as discrete module In wide band gap devices also people are using different heatsink to transfer the heat from the devices. Now different packaging concept which I have already discussed earlier are used depending on the power rating. So I have discussed about two different packaging discrete and the power module.

two different packaging and Kelvin and non Kelvin type under these two packaging ok now If the devices are small discrete elements Small means I have already told under discrete So there can be SMD or TO series which are having like long leads This kind of components can be there If small discrete elements are there Means it is mostly SMD kind of devices Which can be mounted on PCB So SMD devices it doesn't have much more place to connect the heatsink as compared to the TO series or the component which are having long leads So then if it is mounted on PCB so the heat flows via electrical connection or air or PCB tracks can be used as heat conductor So basically the connection let's say in the previous so you have already seen so there are like different connections will be there where the switches will be connected either to the positive terminal or the negative terminal So these leads can be used to take enough heat from the devices or air which is flowing through the device or on top of the device And what is the PCB tracks as I told you so that can be used for heat conductors. This is for small discrete elements which doesn't have the suitable space for connection of heat sink or integration of heat sink. Now if the discrete element is larger in size Larger means it is having long leads And where you can mount heat sink properly So then have a cooling surface Can be soldered on a copper pad or pressed onto a heat sink So there you can connect heat sink properly So the copper pad which will be provided So there enough space will be there for connecting the heat sink Okay.

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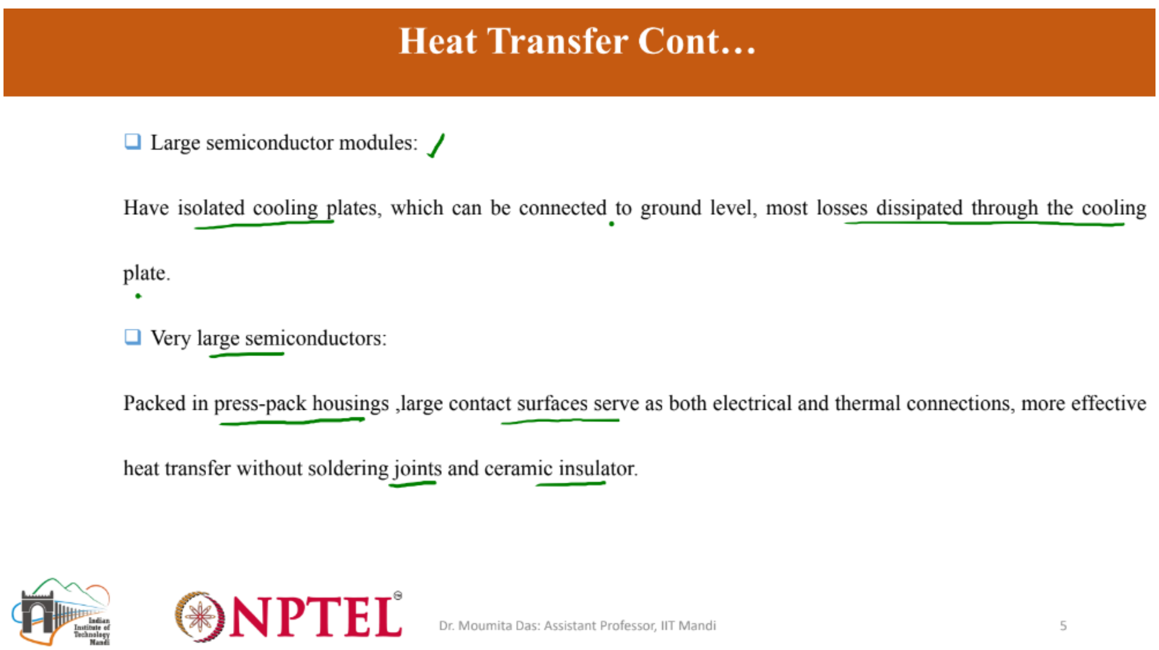

If the large semiconductor modules are there which already I have discussed as power module So then what we can do? We can actually connect isolated cooling plates which can be connected to ground level and most losses dissipated through the cooling plate So because in large semiconductor modules more number of discrete component will be connected So, the heat generation combiningly will be much more than any one discrete component. So, that is why it is important to connect isolated cooling plate. So, that it can take off all the heat from all the devices.

And that is why it can be connected to the ground level. So, that power losses through the cooling plate can be dissipated. Now, if very large semiconductors are there, then it will definitely have the provision for connecting heat sink. So, these are actually packed in press pack housing. Large contact surface serve both electrical and thermal connections and more effective heat transfer without soldering joints or ceramic insulator.

So, this soldering joint or ceramic insulators are required for even for this larger discrete element. It is required for larger discrete element, it is required for large semiconductor modules which will not be required for very large semiconductors. They are already it will be integrated in the semiconductor devices. Okay, so these are different types of heat transfer technique from different devices So these devices either can be silicon or can be wide band gap devices The wide band gap devices mostly fall on this either small discrete element, large discrete element and for silicon carbide large semiconductor modules are also there but very large semiconductors are still not available okay in commercial use.

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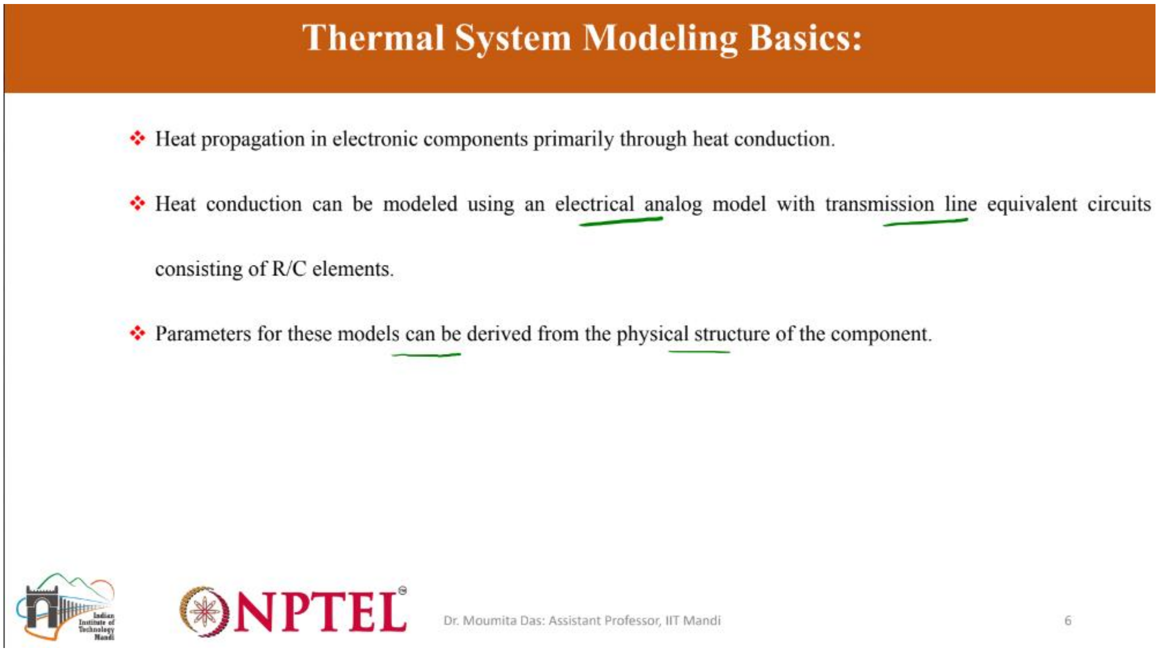

now you can see so thermal system how we can model so in for modeling the thermal system what we need to do heat propagation in electronic component it is happening primarily through heat conduction. So, heat conduction how we can model? We can actually use electrical analog model with transmission line equivalent circuit consisting RC element.

So, electrical analog model if we can use for thermal modeling then it will be easier to model this thermal parameter so the parameter for these models can be derived from the physical structure of the component.

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Electrical Description of Thermal Systems:

- Heat conduction is compared to electrical transmission lines.
- Kirchhoff's analogy: heat conduction processes can be modeled by transmission line equivalent circuits.
- Table of equivalences between thermal and electrical variables (e.g., Temperature ↔ Voltage).

Corresponding physical variables

Thermal		Electrical	
Temperature	T in K	Voltage	U in V
Heat Flow	P in W	Current	I in A
Thermal Resistance	R_{th} in K/W	Resistance	R in V/A
Thermal Capacitance	C_{th} in Ws/K	Capacitance	C in As/V

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so how we can actually model this electrical thermal parameter by considering similarity with the electrical parameter that i am going to discuss now so this thermal parameter generally you know as the temperature T heat flow thermal resistance and thermal capacitance now temperature you know in terms of T it can be either in kelvin or in degree Celsius the unit can be anything any of these two actually So, heat flow generally it is given in terms of P and the unit is watt. So, which we know as the power in case of electrical parameter. So, now thermal resistance it is known as Rth. So, which has unit either in Kelvin per watt or in degree Celsius per watt. And thermal capacitance it is Cth, it is in Ws per Kelvin.

Okay, so now you can see the electrical parameter generally which we use. So, they are voltage, current, resistance, capacitance. So, the voltage is in volt, current is in ampere, resistance is in volt per ampere or ohm and then capacitance is in terms of you can see here As per volts or the means this amperes per volt or farad. Okay. So now you can see here, so the temperature is equivalent to the voltage.

So if we try to model the thermal parameter, so then we have to use temperature in terms of voltage or in place of voltage in electrical circuit. So now heat flow, it is actually flowing

So basically which is generated as the power loss So that we can consider as the current in electrical parameter So current is also flowing from one side to the another side Input to output So here heat is flowing from the particular component to the ambient So in between there will be thermal resistance Through thermal resistance it will be flowing Okay, so now again similarly the resistance will be there in between voltage and current. So, basically so resistance you can see here. So, this is V by I. So, in between this voltage and current this resistance parameter will be there.

Similarly, in between temperature and heat flow this thermal resistance will be there. So, that I will show you in the next slide how it will be there. So, again this thermal capacitance will also be there if it is not steady state condition. If it is steady state condition then the thermal capacitance will not be there. If steady state, if it is not steady state condition then the thermal capacitance will be present.

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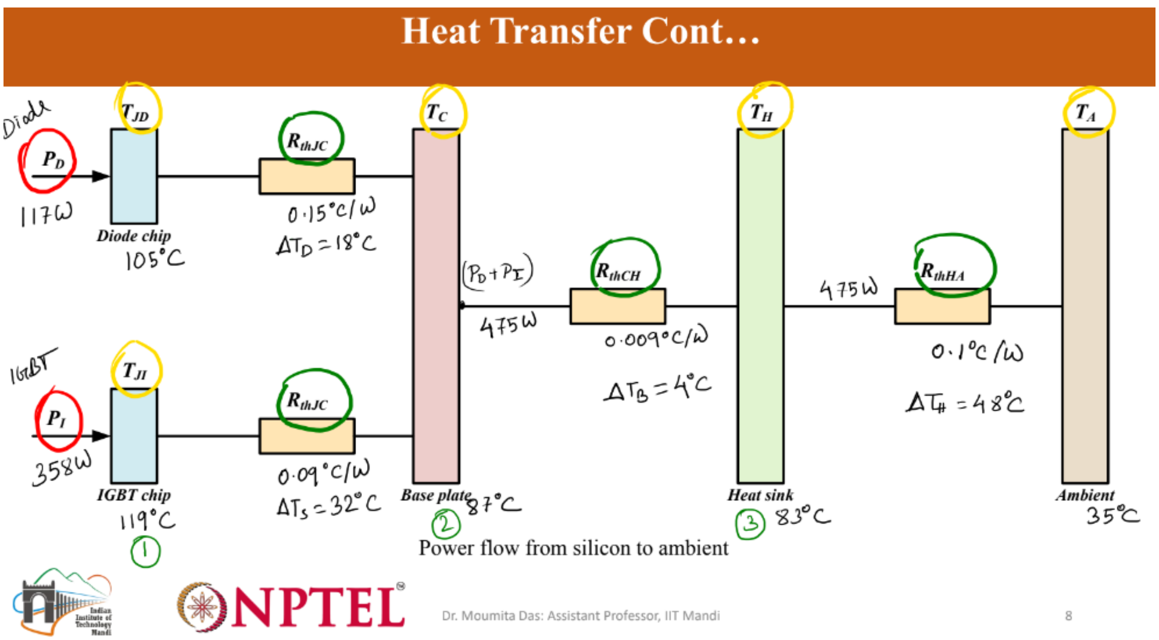

So, I will show you in the next slide how it is going to be. So, you can see here this is the power flow of a silicon device to ambient so it is shown only with thermal resistance because we are considering steady state condition so here you can see this power which we are considering as heat flow okay Now these are this different resistances whatever is present these are thermal resistances. Okay. So let me use different color so that it will be clearly visible. So red one is for power green one is for thermal resistance.

Okay. Now there is temperature, different temperature point which is actually equivalent to voltage. So you can see here different temperature. So yellow one is equivalent to voltage. Because I am considering steady state condition that is why the capacitance, thermal capacitance is not present here. So temperature is like voltage point and the power it is representing as the heat flow and thermal resistance it is equivalent to the resistance of the electrical circuit now we need to model this thermal parameter now how we can model so basically whenever this power or the heat flow is given so basically this power will come from the loss In the device or any component.

Since it is Pd and Pi are shown. So this is PD is the loss with respect to the diode. And PI is the loss with respect to the silicon IGBT. Okay now the power loss. Let's consider the power loss which is happening in the diode.

Which is equal to 117 watt. Let me just use the thinner line. power loss is 117 watt, okay. And then this is in the diode, so this is in the diode and the power loss in the IGBT is 358 watt. Now you know why this power losses are coming in diode and IGBT. Now due to this loss that in the diode chip and the IGBT chip the temperature will be here it is let's say 115 degree Celsius or let's say it is 105 degree Celsius.

And here it is 109 degree Celsius. This 2 temperature is due to the loss which is happening in the diode and the switch. Now, after this diode chip, you can see this point, so there is a thermal resistance. So, let's say the thermal resistance generally is given in the data sheet of diode or the IGBT. So, this will be the thermal resistance. So, basically resistance between the junction to the case.

So, this is base plate which we can access as the case. So, there the thermal resistance which is given let us say this is equals to 0.15 degree Celsius per watt and this thermal resistance of the IGBT is given in the data sheet as 0.09 degree Celsius/Watt. Now, if we have this thermal resistance, so then there will be temperature difference between 0.

1 and 0.2. Let me write down at the bottom, so then the colors will be clear.

This is the 0.1 and this is 0.2. So the 0.1 temperature is 190 degree Celsius for IGBT chip and for diode it is 105 degree Celsius Now because this thermal resistance is present So that is why there will be some temperature drop in the resistance So then what will happen this temperature drop will be the power which is flowing or the heat flow One which is 117 watts in diode multiplied by thermal resistance. So that much temperature drop which generally is known as the voltage drop in the resistance in electrical circuit. So that will be there. So this temperature drop let's say this temperature drop I am writing here it is as delta Td.

So, this will be 117 multiplied by 0.15. So, it will give you a temperature drop of 18 degree

Celsius. Similarly, here in case of switch, the temperature drop will be 315 watts multiplied by 0.09. So, then it will be equal to 32 degrees.

degree Celsius. Because of these two drop the temperature which will be there in the base plate that will be the temperature of 0.1 minus the drop it will be the base plate temperature equals to 87 degree Celsius. Now after the base plate you can see this point the both the points are connected to same thermal resistance That is why the heat flow from diode and heat flow from IGBT in terms of Pd and Pi it will be added in this particular point So this addition will be here Pd plus Pi Okay, so then this will give the heat flow as 475 watts okay now let's say so now after the base plate there will be heat sink so between this also there will be thermal resistance so this thermal resistance so let's say this is equals to 0.009 degree celsius per watt and due to this also this thermal resistance will cause some temperature drop So this temperature drop of base plate will be equal to this 475 multiplied by 0.009 degree Celsius So that will be equal to 4 degree Celsius Now this will cause the temperature at heat sink equal to 87 minus 4 degree Celsius which will be 83 degree Celsius.

Okay, so now heat sink will also have some thermal resistance between heat sink and ambient. So, let us say this thermal resistance is equal to 0.1 degree Celsius per watt. So, same 475 watt will be here at this particular point so then it will multiply with the thermal resistance of the heat sink so then it will create a temperature difference which will be equal to 48 degree celsius then this heat sink temperature 83 will be subtracted Then from this temperature which will be dropped in this thermal resistance Then the ambient temperature will be equal to 35 degree Celsius Okay, so this is what Will be there in the ambient.

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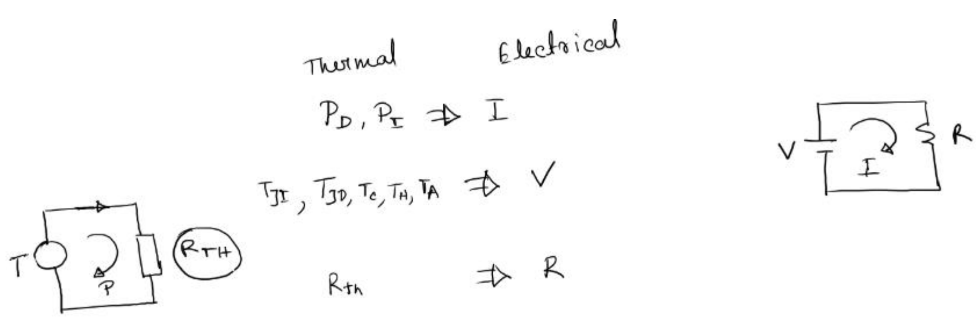

So you can see here So there in the next slide let me just tell you This PD PI These are equivalent to the current in electrical These are thermal This is electrical So generally in electrical circuit Current flows Here this heat flow is there Now this will cause some voltage drop or the voltage nodes So you can see the voltage nodes here are denoted in terms of Tj actually temperature So you can see here either Tjd, Tc, Th, Ta TJD, TC, TH, TA for thermal or here TJI.

So, this is equivalent to voltage in electrical. Now, this current is flowing through some resistances, right. So, basically those resistances generally in electrical circuit we represent in terms of R. Here we are representing in terms of RTHJC, RTHCH, RTHHA. So, whatever representation is there in terms of RTHJC, So, this is CH, JC or HA So, that is actually thermal resistance So, this is equivalent to electrical parameter So, these three parameters are present in static model So, their capacitance is not there So, you can see here Due to the basically in electrical circuit So, the current flows What let's say there is a voltage which is connected to the resistance which cause current to flow. So, basically this V connected to R and then current is flowing.

So, this is with respect to electrical network. And the equivalent thermal network, how it is? So, this Pd, so basically Tj, you have, so I am just drawing the equivalent diagram. So, this let us say this is Tj So, the temperature of any junction or let me just write in terms of T. This T connected to thermal resistance at T h. So you can see the equivalent diagram.

This RTH it is providing the heat transfer medium. It can be heat sink or any other thing which you can use as the heat sink or the PCB track or anything. So this is helping the system to transfer the heat. So T is the temperature you can see here which is equivalent to voltage. P is equivalent to current and R is equivalent to RTH. So, I can also draw this P as like this, similar to this particular diagram.

So, this is how this thermal model we can actually derive. So, this thermal model you can see.

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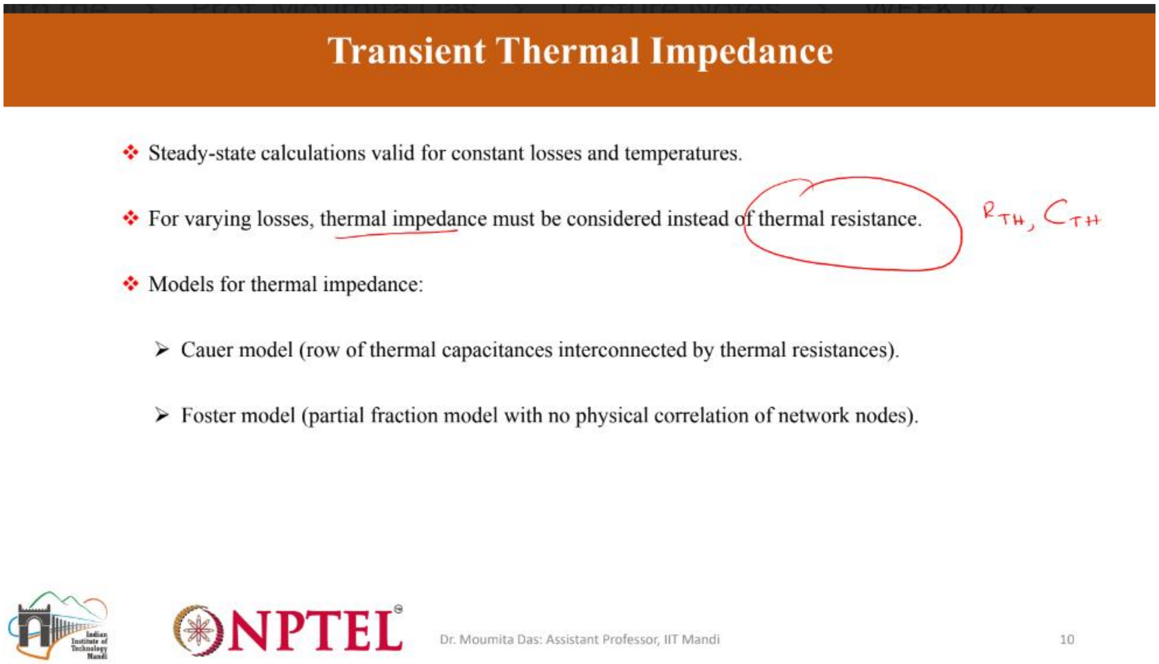

So, this is actually steady state calculations valid for constant losses and temperature. So obviously for initial calculation you can consider the steady state model where we don't have the thermal capacitance So now for varying losses the thermal impedance must be considered instead of thermal resistance So as I told you in place of only Rth we have to consider Cth thermal capacitance This will give us thermal impedance So, for steady state calculation with resistance it is fine. It will give us the idea how this temperature variation will be. But for actual or practical consideration we need to consider this capacitance also.

So, there are two different models which consider these two different parameters resistance and capacitance. One is the Cauer model. Where rho of thermal capacitance interconnected by thermal resistances. Another is Foster model. It is known as partial fraction model with no physical correlation of network nodes.

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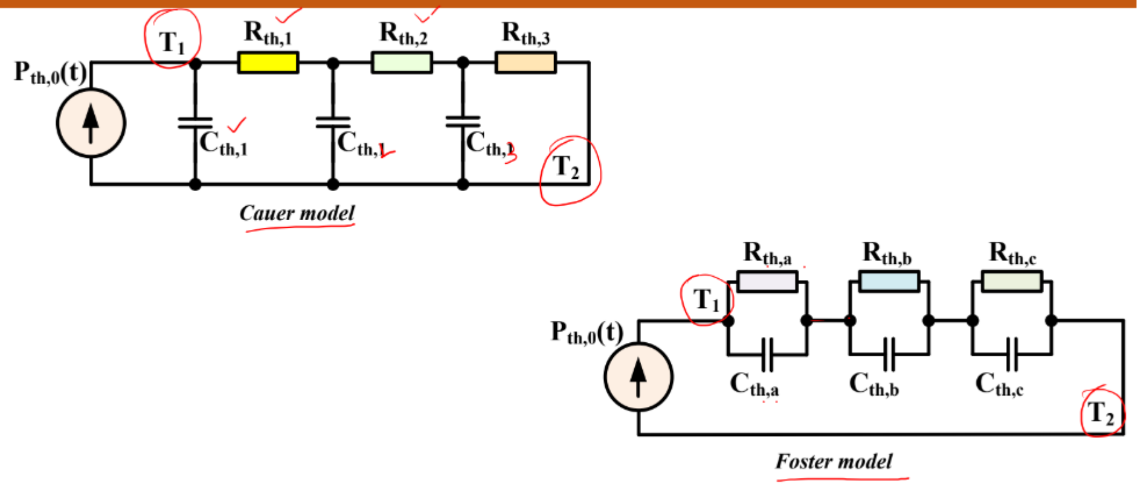
Transient Thermal Impedance Cont…



So, you can see here this is the cauer model and this is the foster model. Here each thermal resistance is connected with the thermal capacitance in this particular manner. So, you can see here RTH1 connected to CTH1, RTH2 connected to CTH2. Here 2, RTH 3 connected to CTH 3.

And this is node 1 and this is node 2. Here the foster model, so this RTH and CTH you can see here connected in parallel. Okay, so this is the node 1 and this is the node 2. So, there are two different kind of model, any of this we can use for modeling our thermal parameter.

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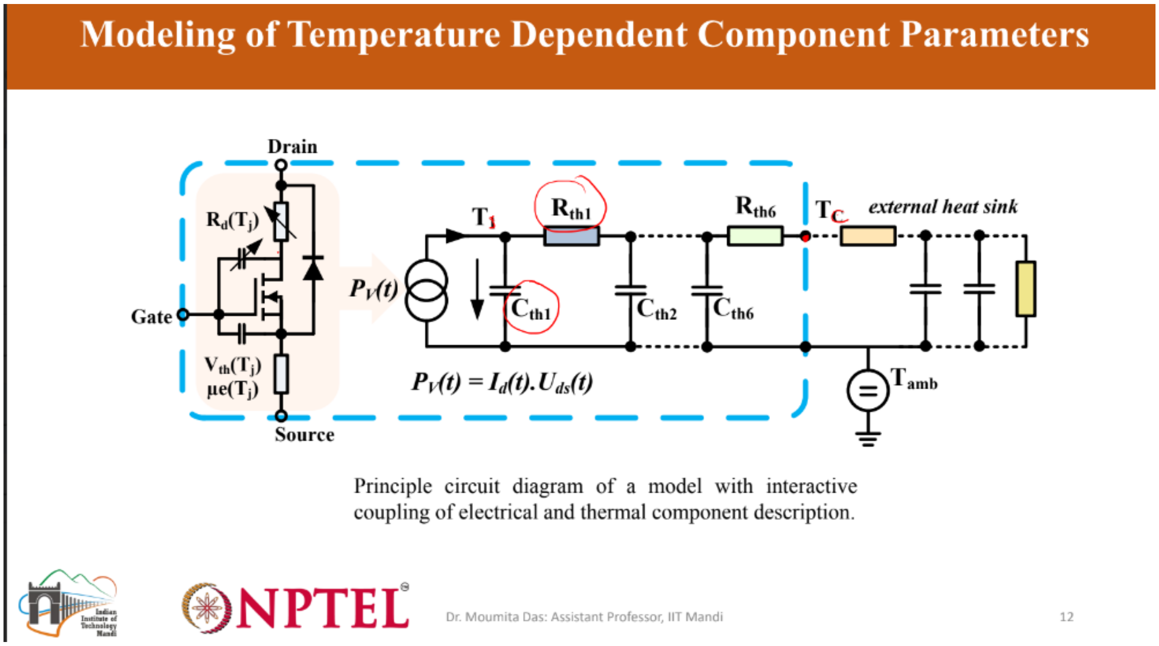

So, this is how we can actually represent any switch. So, if any switch is there, so this particular switch we can represent in terms of, so this is by considering the cauer model.

So, this resistance capacitances and multiple resistance capacitances we can consider and then we will get case temperature here. So, this is the node junction temperature, this is the case temperature and after that heat sink can be connected, okay. So, more about this I will be discussing in the next class. Thank you. These are the references. Thank you.