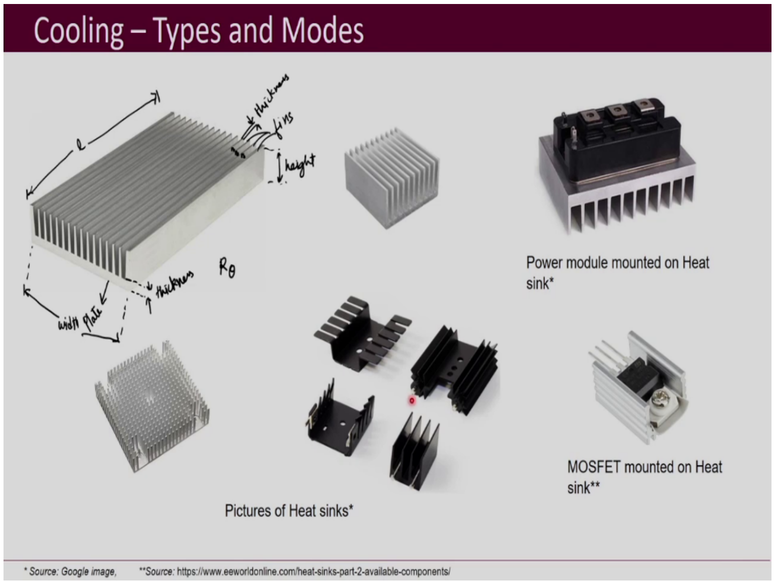
Design of Power Electronic Converters
Professor Doctor Shabari Nath
Department of Electronics and Electrical Engineering
Indian Institute of Technology Guwahati
Lecture 40
Thermal Modelling - I

Welcome to the course on Design of Power Electronic Converters. We were discussing the module of Thermal Design. We had seen how power losses may be estimated for power electronic converters. Now, this lecture, we will see the basic thermal modeling that can be used for choice of heat sinks.

(Refer Slide Time: 00:56)



Cooling – Types and Modes

Power module mounted on Heat sink*

Pictures of Heat sinks*

MOSFET mounted on Heat sink**

* Source: Google image, **Source: https://www.eeworldonline.com/heat-sinks-part-2-available-components/

Now, before going into the thermal modeling, let us look into the different types of heat sinks that are used for power electronic converters. Now, here you can see that, this is an aluminum heat sink, where you have got several fins in it, these are what are called as the fins. So, these all of these, these are known as fins.

And then what matters in heat sinks are how they become different from each other is the thickness of this plate. So, this is this plate which you can see and on that this fins are attached. So, this thickness is very important. And then also the thickness of these fins and of course, the distance between any two of these fins. That means, total how many number of fins are there in this heat sink. And that is of course dependent on the width of the heat sink as well.

So, this width is important as well as the length of the heat sink. Further, what is the height of these fins? This height that also plays important role. And what all these of these things that means your length, your width, thickness, the density of the fins and the thickness of the fins, the height of the fins these all finally constitute the geometry of the heat sink. And plus the type of the material that is chosen for the heat sink.

These decide the thermal resistance of the heat sink. Now, this we will be discussing more further. So, R theta or what is called as the thermal resistance that gets decided by all these things, the geometry and the material. Now, what we see here is that this is another heat sink, and you can see of course, the geometry in the form of shape it is similar, but this number of the fins, the thickness of fins, the dimensions are different.

So, this heat sink performance will be different than this one that is shown here. This is another one which is shown here and this is a power module which is mounted on the heat sink. So what is usually done is that that the module or whatever power semiconductor device we have that is mounted on the heat sink by using screws and in between the surface a pad or thermal pads or thermal grease is applied to connect it to attach it with this heat sink.

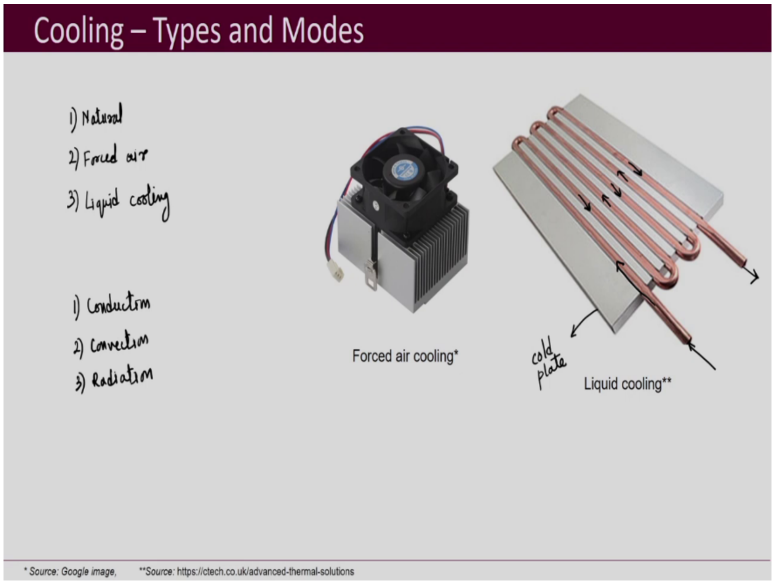
And then this is a module there may be heat sinks, there may be, I mean we may be using power electronic, in any power electronic converter only one device like this MOSFET that is placed on this heat sink. This is a much smaller heat sink. You can see that this geometry of this heat sink is very different from these two that are shown here.

Now, for the single discrete devices, there are other types of heat sinks also you can see here. Now, these are the fins that you can see now, you should see the shape of the fins over here and here and for this heat sink, so they all are very different. So, there are various geometries of heat sinks that are available and you can choose from among them what suits your purpose. Then, this is another heat sink, which is shown here. Now, this is called as the pin fin type.

And here you can see that these fins are not of this type that is shown here, these fins are here like that of some pins. So, there are small, small, very small, small pins that are attached to that metallic plate which is on the bottom on the base. So, in short, we can say that the many different types of heat sinks I have just shown a few of them here there are various other geometries of heat sinks which are possible.

And many times what people do is that they do not additionally attach another heat sink, instead they also use the enclosure of the converter as a heat sink. So, in the enclosure itself fins are port and arrangement is made such that that it acts like a heat sink, and that is also used for cooling.

(Refer Slide Time: 06:34)



Cooling – Types and Modes

1) Natural
2) Forced air
3) Liquid cooling

1) Conduction
2) Convection
3) Radiation

Forced air cooling*

Liquid cooling**

* Source: Google image, **Source: https://ctech.co.uk/advanced-thermal-solutions

There are different types of cooling, one can be natural cooling. Natural cooling means that just the heat sink is put and naturally it will cool down no further additionally, anything is done for the cooling. So that is called as the natural cooling. Second is your forced air cooling, now here your forced air cooling picture is shown here. Now, you can see here that this one is the heat sink and here this fan is mounted.

So, this fan will be rotating and that will help in further cooling down the heat sink. So, that is called as the forced air cooling. Forced air cooling obviously is better in performance than your natural cooling. And then there is other type which is called as your liquid cooling. So, this is the picture of a liquid cooling. So, this one is called as the cold plate.

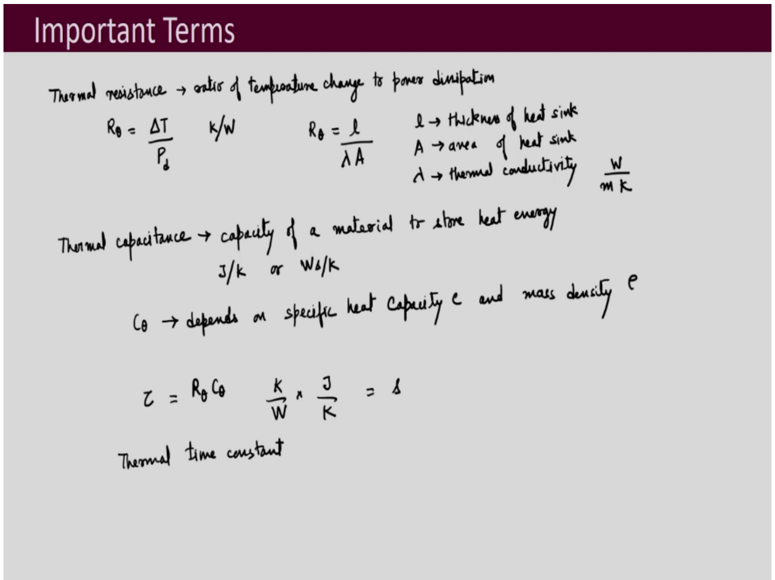
So, it is like this entire plate which is there and through which your cooling is going to happen. And you can see here these are these tubes, the copper tubes, which are going to carry the liquid. So, here the liquid enters here and it comes out from here and through these tubes this liquid keeps on circulating.

Now, different types of liquids can be used, one is of course your water and second is your oil and what type of oil that may be used may vary from application to application. Now, a water has a performance which is better than oil, it is like almost three times more efficient cooling for using water than your oil. But water that has to be used has to be distilled water, means you have to use a purified water no impurities should be there because if there are impurities then that may lead to freezing problem. And also sometimes corrosion may happen because of water.

So, water care has to be taking while circulating water through the tubes. And another is your of course oil, oil does not have this problem of the corrosion problem or the freezing problem, but oil is flammable. So, in applications where oil is used, there again precautions has to be taken so that to the flammable probably have the oil is not creating an issue. Now, cooling when it happens there could be different modes in which the cooling can takes place.

One is your conduction and second is convection and third is your radiation. Now, on these three, you might be already familiar you might have studied in your physics books what is conduction, convection and radiation. In this course, we will not be going into the details of how cooling takes place, because there is lot of theory in it and it is beyond the scope of this course, to go into details of that, we will just take very simple models which can be used by a power electronic engineer to select heat sinks for converters.

(Refer Slide Time: 10:43)



Important Terms

Thermal resistance → ratio of temperature change to power dissipation

$R_\theta = \frac{\Delta T}{P_d}$ K/W

$R_\theta = \frac{l}{\lambda A}$

l → thickness of heat sink

A → area of heat sink

λ → thermal conductivity $\frac{W}{m\,K}$

Thermal capacitance → capacity of a material to store heat energy

J/K or Ws/K

C_θ → depends on specific heat capacity c and mass density ρ

$\tau = R_\theta C_\theta$ $\frac{K}{W} \times \frac{J}{K} = s$

Thermal time constant

Now, let us look into some of the important terms that are required for choosing the heat sink. So, one important term I already introduced you to that that is thermal resistance R theta and it is defined as the ratio of temperature change to power dissipation. So, R theta is given as

$$R_\theta = \frac{\Delta T}{P_d}$$

K/W

Where, Pd is the power dissipation and delta T is the temperature change and the unit is Kelvin per watt.

Now, from this what you can observe is that if R theta is low that means, even for large power dissipation the temperature change will be small. And if R theta is high that means, even if Pd is low temperature change is going to be more. So, for heat sinks obviously, we want that more power could be dissipated and so low R theta are desirable. Further you know that that R theta is given as

$$R_\theta = \frac{l}{\lambda A}$$

Now, l is the thickness of the heat sink, heat sink or whatever material for which you want to calculate R theta and A is the area of the heat sink and lambda is thermal conductivity. Now, what is thermal conductivity? It is a measure of materials ability to conduct heat and its unit is given by watt per meter Kelvin. Now, from this expression what we see is that this R theta is something dependent on the geometry that means, your l and A are also dependent on the thermal conductivity which is a property of the material.

So, the type of the material and the geometry of the material or the heat sink that is what which primarily decide you R theta. Then further another important term is thermal capacitance. Now, this is defined as the capacity of a material to store heat energy and its unit is given as joules per Kelvin or you can also write the same thing as watt second per Kelvin.

Now, this is something similar, you can relate it with the capacitance electrical capacitance that we know about where you are able to store electrical energy their electrical fields, whereas in case of thermal capacitance is like the capacity to store the heat energy. And this if you denote by C theta it depends on two things.

One is your specific heat capacity C and another is the mass density. Now, specific heat capacity C it is again the capacity of or rather the amount of heat energy required to raise the temperature of a substance per unit mass. And C the unit is joules per kilogram Kelvin.

Now, what we see is that that if you multiply these two terms that means your R theta and C theta then the unit that you are going to get,

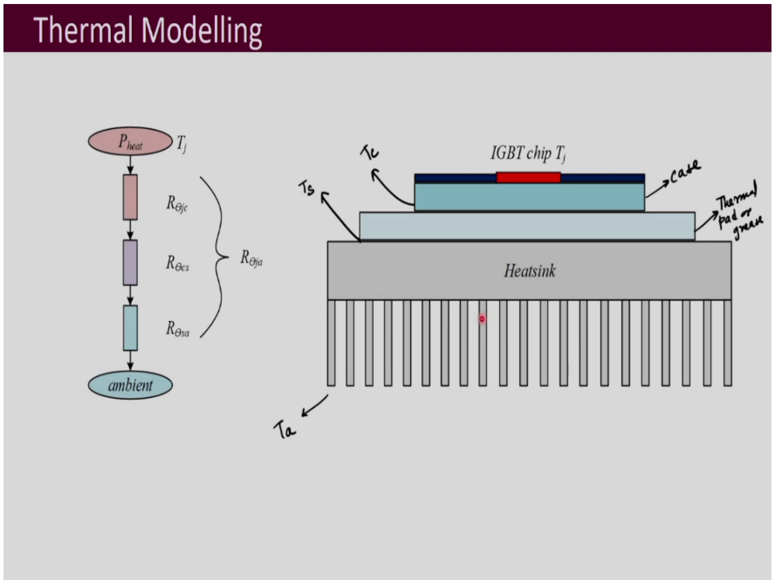
$$\frac{K}{W}\times\frac{J}{K}=\text{sec}$$

So, what you will be getting is the unit of seconds, that means, this is your is a time constant tau this is called as the thermal time constant. Now, this is again similar analogous to the time constant for RC circuits in electrical circuits, where again we use RC as the time constant.

$$\tau = R_{\theta}C_{\theta}$$

So, here we are making an analogy with electrical circuits or electrical equivalent of the thermal performance can be done using this R theta, C theta and this time constant tau and further the temperature drop as well this temperature drop is something analogous to a voltage drop and the power dissipation that is analogous to the current that flows in electrical circuit, we will be looking into it.

(Refer Slide Time: 17:31)



Thermal Modelling

So, here let us see that. So, what here is shown here is that this is your let us say an IGBT a discrete IGBT or a module may be there, where this one chip of the IGBT is shown this is the chip and this one is the casing. And then here this shows your thermal pad or the grease that is applied in between this casing and the heat sink. So, it is like sticking it, sticking the module or the transistor to the heat sinks or phase.

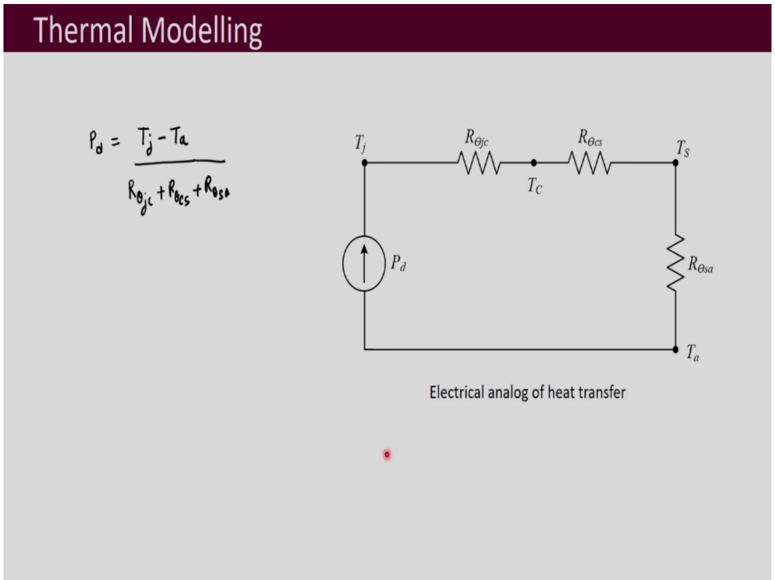
Of course, it has to be screwed, I mean, the module or the discreet device has to be screwed to the heat sink, but the thermal paste or a pad is also applied in between them. So, this is the thermal pad or the grease and this is the chip. So, this is the case and this is your heat sink. Now here, let us give different names to the different temperatures. So, this one is the junction temperature Tj of the chip. And here there is this case temperature which is the Tc, this one is the temperature of the heat sink Ts.

Now, each one of these have your thermal resistances. So, what we can name it as between your junction and the case, here the thermal resistance is denoted as R theta jc and between case and this sink that can be denoted as R theta cs. And of the heat sink that is heat sink to the ambient, so ambient will also have its own temperature we can call this Ta, the ambient temperature.

So, when your this Ts and Ta, we can say that the resistances R theta sa that is synced to ambient is basically the thermal resistance of the heat sink. So, we can model it like this that the heat which is, which actually flows from this chip because heat, this is where all your conduction losses and switching loss takes place.

And then here heat is generated and then this heat has to be dissipated in this device has to be cooled down. So, from here to here, the cooling happens. So, the heat gets dissipated from this. So, this is like we can make a diagram like this. Now, what we want is that we want to represent it form of an electrical circuit.

(Refer Slide Time: 20:43)



Thermal Modelling

$$P_d = \frac{T_j - T_a}{R_{\theta jc} + R_{\theta cs} + R_{\theta sa}}$$

Electrical analog of heat transfer

So, that is what is shown here this is electrical analog of the heat transfer. So, this power dissipation Pd is modeled as a current source and this temperature as I told you is analogous to voltage in electrical circuits, so your this is the voltage or rather the temperature of junction temperature Tj and you have this point Tc then Ts and then Ta and in between them the thermal resistances are put here R theta jc, R theta cs and R theta sa.

So, now, then we can write Pd as equal to the dissipated power as equal to

$$P_d = \frac{T_j - T_a}{R_{\theta jc} + R_{\theta cs} + R_{\theta sa}}$$

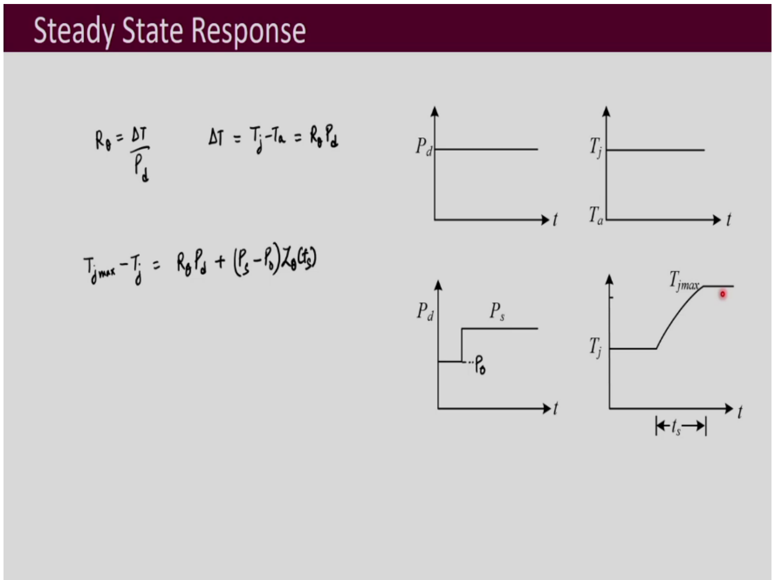
So, now when we have to choose this R theta sa that means the heat sinks how much should be the thermal resistance of the heat sink, we have to decide that.

So, what we will be doing is that we will have an idea of the ambient temperature because whatever application is where you are going to use your converter, you will know what will be the ambient temperature approximate ambient temperatures and based on the devices you have selected. When you go to the data sheet, then you will see the Tj the maximum junction temperature that the device can withstand.

And junction to case thermal resistance that is also specified in the datasheet of the devices. So, you will obtain this R theta jc from there and this R theta cs is based on your what thermal pad or grease whatever you are using, applying that also usually, you will be able to find out. So, then these two are known that means your R theta jc and R theta cs these are known and Tj and Ta this is also known.

So, and what is the maximum power dissipated that also you can estimate that we have looked into how much power losses are taking place in the devices that you can have an estimate of it and from there you have everything in this equation. So, you can find out what could, what is good value of R theta sa, that we will be able to limit this Tj below the maximum junction temperature that is specified in the datasheet.

(Refer Slide Time: 23:49)



Steady State Response

$R_\theta = \frac{\Delta T}{P_d}$ $\Delta T = T_j - T_a = R_\theta P_d$

$T_{jmax} - T_j = R_\theta P_d + (P_s - P_0) Z_\theta(t_s)$

The further when your thermal losses takes place power dissipation happened then at that time, there may be various variations in it, like for example, when you starting the converter and you are shutting down the converter or you were operating at one particular state and then you took it to another state. So, this is like once in a while changes that may be happening and those may also lead to changes in the power losses and heat and so the temperatures.

Now, these are relatively slow variations. So, this is called as the thermal cycling. And that took has their own problems associated with what kind of failures may happen, how many number of times thermal cycling in the devices can withstand, so or the different whatever components that are used, how many number of times they can withstand the thermal cycling.

So, that can be looked upon. And then there is the power cycling that means your regular power dissipations that are taking place the ups and downs that are happening in them in a very frequent basis at a much higher frequency. So, in that we can have two types of responses, one is your steady state response and another is your transient response.

So, steady state response here is like that you whatever power dissipation is happening that is taking place in a fixed manner or fixed rather we should say is in a pattern and that is continued. This is similar to the steady state and transient response that we talk about in electrical circuits. So, let us say the power dissipation graph that is shown.

So, with respect to time t, this power dissipation is fixed it is not changing. So, then from this R theta equation which is

$$R_\theta = \frac{\Delta T}{P_d}$$

$$\Delta T = T_j - T_a = R_\theta P_d$$

So, if Pd is fixed not changing with time, so, delta T that this difference between in the temperature Tj minus Ta this will be also fixed. So, that is like a steady state, it is being maintained.

Now, similar situation you can see in this case also where the dissipation of the power let us say first it was at some level P0 and they need to reach to any third level which is your Ps. So, initially while let us say this was maintained for quite some time, so at that time the junction temperature was over here, and then when this sudden transient came up, it changed this power dissipation. So, it will take a while for it to reach to the next junction temperature, we call it as Tj max.

And in between there is a transient temperature will increase and then it will again reach to the steady state. So, for this graph, we can write Tj max minus Tj as equal to

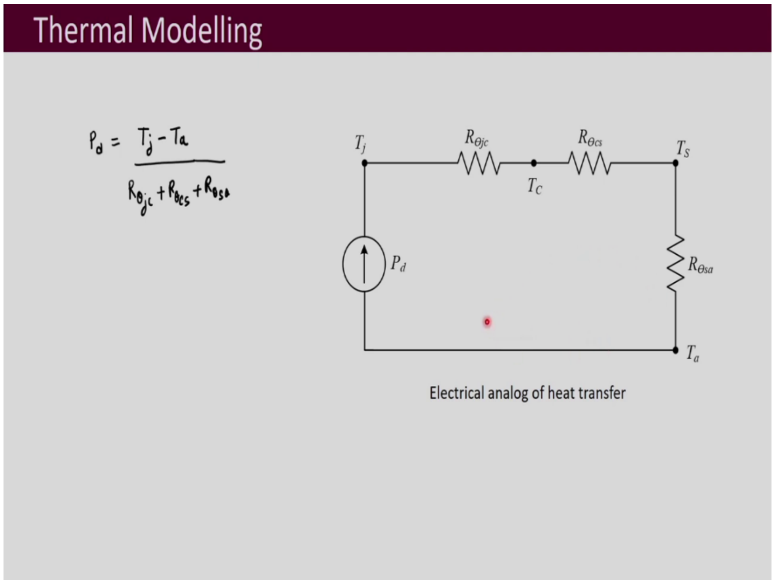
$$T_{j\max} - T_j = R_\theta P_d + (P_s - P_o) Z_\theta (t_s)$$

Now, ts is this time interval and Z_θ is your transient impedance, the thermal impedance this we will be discussing a little later.

So, what we see here is that that this part is the temperature rise which is of transient in nature and this part R theta Pd this one is the steady state part. So, finally, when here it is in steady state, so this here R theta Pd that is the temperature that will be obtained. And this ts it is like your time constant your what we saw just a while ago, that is multiplication of your R theta and C theta.

So, higher the time constant the more time it will take to go from one steady state to another steady state means more will be the time of the transient. And smaller is the time cause that will it will quickly reach up to the next steady state. So, this time constant also then that is important while your power dissipation levels maybe change.

(Refer Slide Time: 29:10)



Thermal Modelling

$$P_d = \frac{T_j - T_a}{R_{\theta jc} + R_{\theta cs} + R_{\theta sa}}$$

Electrical analog of heat transfer

Now, steady state response can also be looked upon in a situation where let us say this the power is pulsating this Pd what we see here this graph is a pulsating nature, but the frequency of these pulses is so high that with respect to the time constant of the corresponding semiconductor device, that the junction temperature is not able to change much because the junction temperature has got its own inertia, the whatever the device the junction that is had a chip it has its own thermal inertia.

So, it takes some time for it to change because of its own whatever the time constant is there. So, here what we see here is that that this is the junction temperature this is how it is varying, it is slightly increasing decreasing. Here, you can see that here it increases for this much interval and then for here to here for this time interval it is decreasing. And this increase and decrease may not be very high.

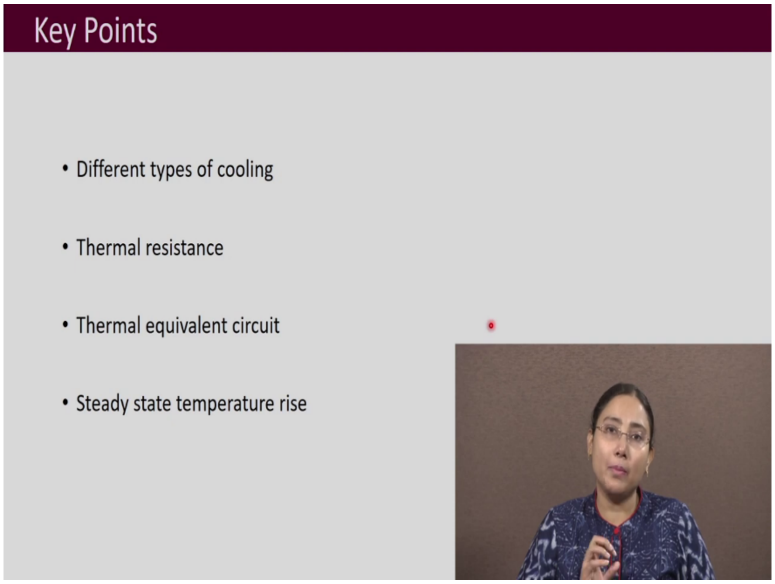
So, it is like the junction the chip is reacting to the average rather than the actual power dissipation that is taking place the huge amount of change that is happening in the power dissipation at a high frequency to that the junction is not responding, it is actually responding to the average power. So, this also is like the steady state only, I mean it is taken as a steady state response and it is this average of this is what we can take it as the junction temperature.

So, here your junction temperature Pd we can say that it is the average temperature, average power dissipation to which it will be responding in that will be Tj minus Tc the case temperature divided via R theta jc. Now, this R theta jc means the thermal resistance of junction to case is what can be used in this case and then this if it is steady state that means, that will be equal to Tc minus Ta R theta cs plus R theta sa we can write like this.

So, then as I have told you before that you know different other temperatures and so using this then you can find out what will be the sink thermal resistance that will be required. So, in case or in situations where a steady state response is valid. In those cases the thermal resistance concept can be used to select the heat sink.

We can substitute other values and if the let us say the power dissipation units like this it is pulsating, but at a very high frequency and the time constant of your junction to case is relatively more as compared to the frequency at which these the power dissipation is pulsating. In that case, the steady state response the equations like this or this electrical circuit, this electrical circuit that I shown you can be used for choosing the heat sink.

(Refer Slide Time: 32:41)



Key Points

- Different types of cooling
- Thermal resistance
- Thermal equivalent circuit
- Steady state temperature rise

So, the key points of this lecture are that there are different types of cooling your natural, forced air and liquid cooling. And depending on the application and especially the range of power, your type of cooling is chosen for small power low power levels natural cooling is sufficient as the power level goes up then we have to go for forced air cooling and further when the power level becomes very high than that time even forced air cooling does not work we have to go for liquid cooling.

And thermal resistance is a very important parameter in choosing heat sinks. And then we can use a simple thermal equivalent circuit if a steady state response is valid for the type of power dissipation that is taking place. And in case of your steady state temperature rise as I just showed you that the temperature is like going to a particular value and it is being maintained that that is it is steady, it is not changing very quickly with respect to time. Thank you.