Power Electronics with Wide Bandgap Devices
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Lecture-31
Power Density (Part 02)

Welcome to the course on power electronics with wide band gap devices. Today I am going to discuss about the calculation of the power density or how the different factor affects the power density analysis of that. So this will be part 2. So basics of this power density I have discussed in the last class. So let's see what are the factors which affects power density. So as you already know the power density how it gets affected by different parameters in the network.

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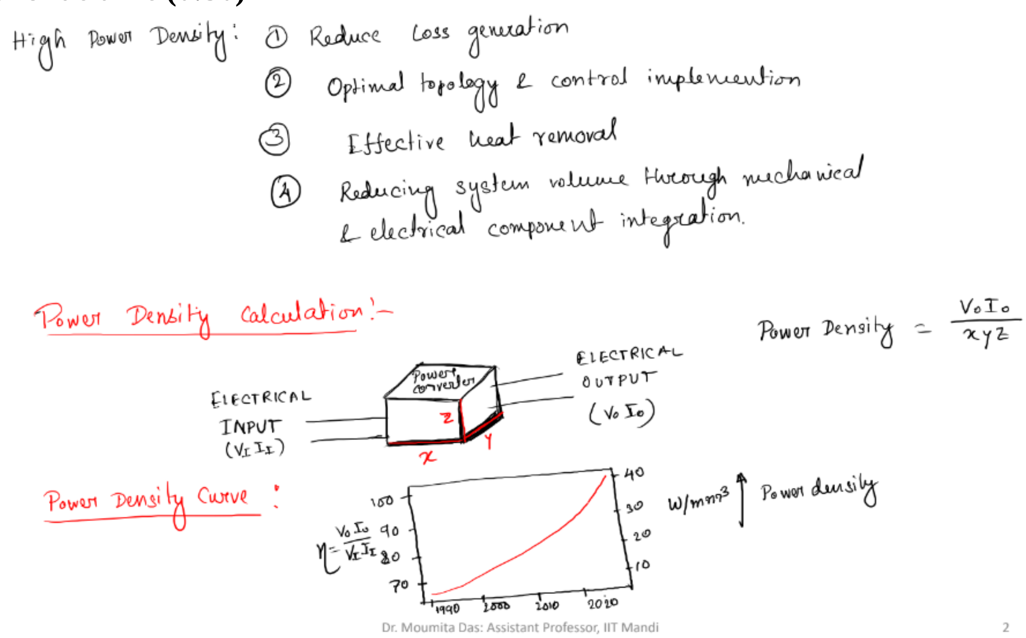

So they are so basically for achieving high power density. So the different factor which affects it are so basically need to reduce loss generation in the system right. So different types of the loss which are generated in the system that need to reduce down so that power density can be improved. Second is the optimal topology which I have mentioned as advanced circuit topology.

So this selection and control implementation will help to achieve high power density system. Third is that effective heat removal or thermal management. Okay, so that need to look after. Fourth is that reducing system volume through mechanical and electrical means. component integration.

So these are the parameters which need to be considered or look after so that high power density can be achieved, right. So, this already you know. Now, how to analyze these things, these different parameters? So, if we consider any power electronic system as black box, so then it will have three different axis. with respect to height, length and width so let me just draw the power converter it can be any power converter it can be optimal topology or maybe normal conventional power converter so whatever it is so then so power density if we want to calculate and how we can do that so let's consider this is this let's say one black box with respect to the power converter right This is output and here comes the input. So, this input and output, these are electrical input and electrical output.

So, let me just write down. And this is power converter. Right. So, now if we have to calculate the power density then let us represent these three different sides. So, this let us say this is x this is y and this is z right these three different sides basically.

So then the power density formula we can write down as equals to this electrical output if we represent as V0 multiplied by I0. So, whatever power will be at the output. So, this V0 I0 divided by x multiply y multiply z, basically volume of the system or the power converter. So, this will give you power density.

$$PowerDensity = \frac{V_O \cdot I_O}{x \cdot y \cdot z}$$

Right. So generally the unit of the power density as I mentioned in the last class. So that is watt per millimeter cube or inch cube or centimeter cube. So you can see this V0 I0 will give you watts and then xyz will give you either millimeter cube centimeter cube inch cube. So whatever unit you are taking.

Right. So this will give you the power density. Then you can calculate. So you can just calculate the power output. So, whatever output you are getting and then you can measure this x, y, z and then you can quantify what will be the power density of the system, right. So, now this power density, this power density, now if I represent it in graph, so then this can be represented as, let me just draw the graph of this so there are actually three different factors which we need to consider right so these factors are how this power density is varying And then how the efficiency of the system is changing with respect to that.

And how this progress is happened. Basically this history of this power density if we try to represent. So then let's say this is 10, 20, 30, 40. This is in watt per millimeter cube. this axis actually defines power density.

Then the efficiency if we try to see for any system, so the efficiency which is actually represented as be, like b0, i0 divided by vi, ii. So basically output divided by input. That will give the system efficiency so that if we can represent like this 70, 80, 90 let's say 100 yeah this is efficiency of the system so if input if we represent as viii so then this will be equal to v0 i0 divided by viii okay now the progress of this semiconductor devices is starting from 1990 it is like now we are in the into 2024 so if we try to plot that so the year if we represent here is in 1990 then similarly let's say 2000 then here 2010 then 2020 Then if we try to represent this, then we will see this curve, it actually looks like it is increasing with time. So, you can see here in 1990, like if we try to like see from 1990, so the efficiency and the power density both were in the low side, means efficiency was also low and the power density was also low. As the time progressed, so you can see the efficiency also increased and the power density also increased and this is due to the development, one part of is due to the development of this wide band gap devices there are many other factor like high frequency operation this enable high frequency operation and also thermal management and like designing the layout pcb layout using like different passive components so basically i will discuss about this different passive components how this power density factor changed for different passive components that i will discuss so different factors helped the system to go towards high efficient and high power density system, right.

So, this is actually shown in this power density curve. So, now let us see. So, now if we represent, so this black box, Whatever I have shown here, you can see here this x, y, z. So, now if I try to see the temperature difference which will happen in the system, in the converter. So, there will be ambient temperature and the surface temperature of the converter.

Means converter if it is placed in a box. So in the converter there will be different power losses. One due to active component and due to passive component. Passive component considering the inductor, capacitor, resistor, those whatever is present in the converter. And the active component which considers the switch and the diode.

So, different losses will cause heat generation. And there will be difference in the heat which is generated in the converter. If you consider that is a black box. And the ambient temperature. So, how that is? Let's see.

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Thermal Analysis :-

$$\Delta T = T_{surface} - T_{ambient} \quad (K \text{ or } °C)$$

① Heat convection for a black box :-

$z = h$ (height)

$y = l$ (length)

$x = w$ (width)

$$P_d \text{ (convection)} = 10^{-3}\left[4.6(l+w)h^{0.75} + 1.8(l \times w)^{0.75} + (l+w)^{0.25}\right] \times \Delta T^{1.25}$$

② The surface radiated heat transfer is given by :

$$P_d \text{ (radiated)} = 3.66 \times 10^{-11} \times f \times e \times A\left[T_{surf}^4 - T_{amb}^4\right]$$

A → Surface area in inch

e → emissivity $= 0.9$

f → View factor $= 0.5$

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So, basically we can actually quantify that. So, basically thermal analysis if we do. thermal analysis of any converter, any system which is having a height, width and length, specific height, width and length and that can be variable, right. So, then we can represent this delta T, the thermal basically temperature difference delta T will be T surface of the converter of the black box minus T ambient. This unit can be either in Kelvin or in degree Celsius.

Okay. So that depends on like which unit you are using for the calculation. Right. Now if we try to find out this T surface.

$$\Delta T = T_{surf} - T_{amb}$$

So basically it is having two component.

Heat generated. So basically heat. So T surface will have two different component. One is one part will be heat generated. convection for a black box. So, here in this case let us consider z represent the height then y represent length of the box and then x represent width of the box.

So, these are the length. this can be any box like if you have like any box three dimensional so it will have this height length and width and there will be like five surfaces five sides through which it can actually dissipate the heat right so the bottom one which will be connected where the devices will be connected so that will not be in use so there will be six different sides of the box out of which five can be used for heat dissipation so then This heat convection we can actually find out P effective for convection is equal to

$$P_{d(max)}^{cov} = 10^{-3}\left[4.6(l+w)h^{0.75} + 1.8(lw)^{0.75}(l+w)^{0.25}\right]\Delta t^{1.25}$$

okay so these are the different factors so you can see from here okay so you can actually see from here so this length height and width of any system so basically the box which I have drawn in the previous page so it is having five different basically six different sites out of which This five different sides, you can see this one, this one, this one and other two sides of this, this and this here, this. This five sides, the bottom one will be connected. So, this five sides will be used as the T surface. So, temperature where it will be effective temperature.

So, through the convection, okay. So, this convection temperature, effective power loss in the convection. So, basically heat generation can be calculated. by using this formula so whatever height length with the system has based on that the convection can be calculated power in effective power in the convection can be calculated similarly so there is another component so heat so basically this surface radiated heat transfer is given by This is given by Boltzmann equation. So, Boltzmann by following Boltzmann law.

So, this can be calculated. So, this is P radiated if we effective radiated. So, this is radiated. This can be write down as

$$P_{d(max)}^{rad} = 3.66 \cdot 10^{-11}\, feA(T_{surf}^{4} - T_{amb}^{4}),$$

So, this is here in this, this is surface area, okay.

So the unit is given considered here is in inch. If you want to consider different unit accordingly that factor will change. Then this is emissivity. So this is generally considered as 0.

9 and this is this factor F. So this is view factor. This is considered as 0.5. Right. So this is this different like factor will give you that radiated effective radiated power which will be like due to that particular system and that will give the surface radiated heat.

One will give heat convection and one will give radiated heat. Heat radiation, heat convection. Okay. These two different heat component will finally give you the total heat generation in the system.

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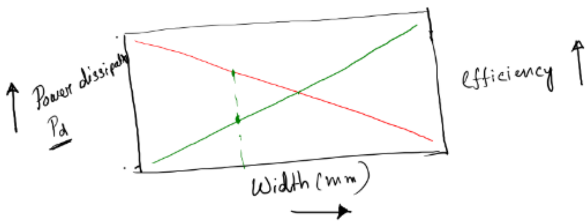

For a given system if h & w are constant then length can be selected.

$$\eta = 1 - \frac{P_I - P_o}{P_o} = 1 - \frac{P_d^{max}}{P_o}$$

$$P_d^{max} = P_d^{conv} + P_d^{rad}$$

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Okay. So, now how we can consider? So, you have seen this height, length, width everything is given. So, we can optimize the system parameter means like if we have to increase the power density so then system optimization is required then what factor we can optimize so let's say that any of the two factor in height length width is given already and the other factor we can actually change based on that we can see that how this efficiency or power density will be affected so basically you know the curve which you can draw like power dissipation which you can represent as PD right the power dissipation is related to height length and width right so now this if it is like width of the system millimeter and this is efficiency Efficiency is related to power loss right. So then if loss increases then efficiency will reduce. Now this loss is again related to power generation and dissipation. If whatever power generated if it is not dissipated so then it will again cause increase in the heat further heat and then efficiency will get affected.

$$P_{o(max)} = P_{d(max)} \cdot \frac{\eta}{1-\eta}.$$

$$P_{d(max)} = P^{cov}_{d(max)} + P^{rad}_{d(max)}$$

So that is why this can be drawn so like power dissipation it is increasing Let me just use different color so it will be visible properly It is decreasing as with you can see here so this actually says this width is increasing right Then what will happen? If width is, this is power dissipation, it is increasing in this side, efficiency it is increasing in this side. If width is less, then what will happen? Power dissipation PD is maximum, that is it is not dissipated, right? So, then dissipation, so if width increases, so then what will happen? You can see here this power dissipation is very less here. So, if width is very less, then power dissipation will be more and width is less, then the power dissipation decreases. Sorry, if it is more then the power dissipation will be less. And the efficiency part if I try to draw, so it will increase.

If width is increasing then efficiency is also increasing. Now you can see there is a cross section where basically two are like same this particular point but if we choose any point here so basically based on this particular width so we can see what will be the power dissipation and what will be the efficiency for that particular width right. Now if in case any system where length so height and width are constant so for any system for a given system if height and width are constant then length can be selected selected as per the requirement so that is up to the designer so now this efficiency factor if you see how it is related so efficiency is 1 minus p i input minus output by p output Now this can be represented in terms of P dissipation. So I minus output so that is the power dissipation. So this can be PD maximum so the power dissipation so which here it is written as PD, PD maximum divided by P output right.

So, then, so you can see here, so this power dissipation minimum, so basically whatever minimum or maximum based on that this efficiency level will vary. So, this can and now this PD maximum, so this is here PD will be minimum and this is where PD will be maximum. So, PD maximum it is related to PD convection plus PD radiation. So, this I have discussed in the previous part. So, this effective radiated and the effective convection.

So, this if I represent now in terms of PD. So, you can see here. So, just let me use the same color. So, this is PD radiated and this is PD convection. So, these two will give us total Pd power dissipation, right. So, this based on the length, height, width and different factor we can calculate this Pd convection, Pd radiation that this will give you total power dissipation and this power dissipation is required for the calculation of the efficiency.

Now, this power dissipation for given length, height, width it is same like like if everything is constant then we cannot do anything but if like two parameters are constant so this two parameter as you can see from here height and width if it is constant then if we change the length so accordingly PD convection can be variable if PD convection is variable then PD maximum is also variable accordingly efficiency can be adjusted so that is how we can actually see what will be the power density and the efficiency in the system so we can actually modify this different parameter and then accordingly we can optimize the power density of the system is it clear so this is required only to just find out like how this efficiency and power density will be related now if i now you have the idea like how these different factors are coming into picture but This all gets affected by the losses. So now if we try to quantify different losses. So now let's say power converter losses. Power dissipation again will be related by the power converter losses.

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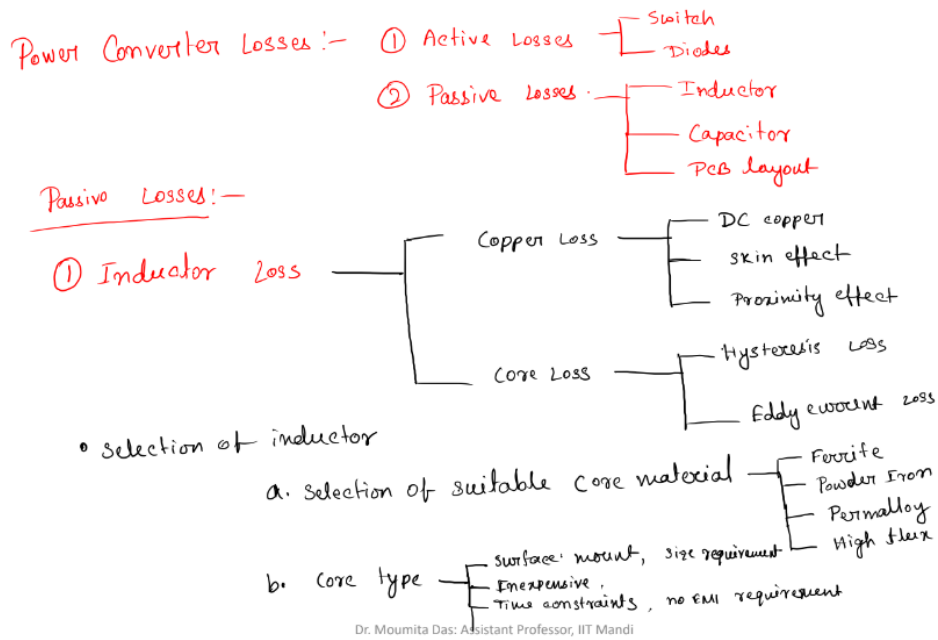

So how this power converter losses we can optimize. So if the losses the converter if it is less then the dissipation again it will be less affected right so like loss less than the dissipation for using convection and radiation whatever is given for a system height length and width that may be sufficient so if we can optimize the loss in the converter then the given length height width will be sufficient if the losses are more then we have to work on that particular part so that we can actually dissipate the whatever loss is happening in the circuit okay so the power converter losses we can actually quantify this already I have discussed so there are actually two different losses active losses and passive losses So active comes under like so like different switch semiconductor devices wide band gap semiconductor devices also comes under this and the diodes right and the passives it will be inductor capacitor mainly these two parameters because resistance is something which is like which is not actual component. So, these are the parasitic basically due to some ESR or like inductance. So, parasitic resistances can be present, right. Other than that these two components mainly comes into picture.

Let's start. So you already know the switch losses. So there will be like conduction loss, switching loss, reverse recovery loss that I have already discussed in the last class. So that calculation also you know that you can find out from there. Now let's see. what are the passive losses so generally when you consider inductor or capacitor these losses we consider like there may not be very significant kind of losses but if we try to see like inside of these different passive elements then it will be easier to find out how these losses are coming into picture so I will just discuss passive losses Okay, so now first consider inductor loss. First what is that? Inductor when I consider so this means magnetics so basically magnetic related losses so this again Can have like inductor a couple inductor transformer any magnetic component can be there so the losses Which we need to look in this particular component they can be classified so basically into two categories mainly copper loss and So, then and core loss.

Again you can go to the basic of this like how you can actually calculate different copper and core losses in the magnetics. Now copper losses you can actually find out. So, basically DC copper loss, then skin effect, proximity effect. so dc copper loss probably the thing is this is the thing generally mostly we consider under copper loss but skin effect proximity or effect also we need to consider when we are designing any converter Because you know like designing PCB that is actually one of the main important part. So there how the lines are placed and then line current will give this like will there be skin effect and proximity effect.

And because of that this again like there will be losses it comes under the copper losses. You can go in details of this I am not discussing further. So like you can see in details of this particular component. So to know that how this losses can be calculated. Now core losses you already know about this also hysteresis loss and eddy current loss.

So, this different loss component calculation, if you want to go through, go through any book, basic book where this magnetic losses are given, there by using the formulas you can easily calculate. Okay. So, these are the different losses. Now, these losses will be there. But then how to select this optimum kind of inductor? So, there are also other factor which we need to look after.

So, like any inductor will have these losses, but how to optimize this inductor in the system. So, that depends upon first thing is that by selecting, selection, just a minute. This depends on the first thing is that selection of suitable core material. When I say core material, so there are different types of core materials, right? Some are suitable for low frequency, some are suitable for like the frequency which is medium, some are suitable for high frequency. Now as I am discussing this wide band gap devices, so the material which is in use for silicon based applications that may not be suitable.

So, that is why we have to select the core material which is suitable for high frequency operation. This will again give us losses. So, related to this copper and coal losses much lesser, right. So, what are these different core material? So, these different core materials are. So, basically some I am just telling you, you can see the advantage and disadvantage of these different core materials.

So, ferrite is the most commonly used core material for silicon based application converters, right. High frequency silicon based like converter which is operating in 10, 20, 50 kilohertz in that level. So, there is also the core material which is suitable for high frequency application, they are powder iron converters. So powder alloy So basically it is This is high flux core and So, there are different types of core materials are available. So, you have to select suitable core material which will give you these different losses very less.

This is with respect to the core material. The second thing is that selection of the core type. What kind of core you will be selecting? So, basically core type. shape of the core so there are like core shapes which is available E type of core like E shapes U shape then pot core now there are like integrated kind of magnetic core are also available so based on this different integration like different core type what you can you can select suitable like core for particular application whatever application you are considering this will actually you need to consider so when you whatever type of the core you are selecting it is if it is surface mount then obviously it will require less space right because we are considering here a high power density so then surface mount will give you less requirement of space inexpensive Again, the cost we have to optimize.

Right. Then, time constraints. Right. Another thing. So, I will write here only. This is not possible to write here. Okay. So here I am writing this will again like surface requirement it is related to size requirement.

And this another factor here it will be no EMI filter requirement. So this different factor you need to consider when you will be selecting code type. For achieving high power density.

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2. Capacitor Loss :-

	Electrolytic	Tantalum	Ceramic
1 uF	1 Ω	2 Ω	20 mΩ
100 uF	50 mΩ	1 Ω	45 mΩ

ESR

Input capacitor loss :- $P_{Cin} = \left(\frac{I_{OUT}}{2}\right)^2 \times ESR_{IN}$

Output capacitor loss :- $P_{Cout} = (\Delta I_{OUT})^2 \times ESR_{OUT}$

Right. Okay. So this is with respect to the magnetic component. Another component or the inductor which is present in the system. Another is the capacitor. Capacitor losses. So let me just. Generally when we consider capacitor, so then we can represent capacitor it is having some ESR, capacitor with ESR.

So, depending upon the value of the capacitor, this ESR parameter will change. Now, how to select this capacitor? Is there any factor which affect this capacitor ESR? Because this ESR component is very important in capacitor that will cause the power losses. Now, if you see the capacitor, so there are like different types of capacitor is available. commercially so what are those capacitors so if you see there are capacitors which are available commercially they are it's a electrolytic tantalum ceramic now If I need 1 microfarad capacitor, so this is just an example. For 1 microfarad capacitor, how this ESR is going to be affected for different type of capacitor? So, you can see if I choose 1 microfarad electrolytic capacitor, it is having ESR around 1 ohm, right? Now, if I can select tantalum, so then the ESR will be around 2 ohm.

Right, now if I can select ceramic then it will be 20 milli ohm. Right, now if I have to select 100 micro farad for some application. So, then the electrolytic will have 50 milli ohm ESR, tantalum will have 1 ohm and ceramic will have 45 milli ohm. So, for different value of the capacitor this will change. You can see for ceramic the ESR is less. So, then this will give like better result with respect to other two capacitor parameters which is given here.

So, now this capacitor it is actually required in both input and the output. So, this input capacitor losses if we have to find out input capacitor losses, Losses if we have to find out Pc in it is equal to I out by 2 square into Esr in. Now if we have to find out output capacitor loss. then it will be Pc out equals to delta I out square multiplied by Esr out. So, these different resistances it is known as Esr.

Right, accordingly we can actually calculate that losses in the capacitor. Now, another third important thing which comes under passive loss which is PCB layout. Inductor and capacitor I told you. So, here in the passive losses, here one component will be PCB layout.

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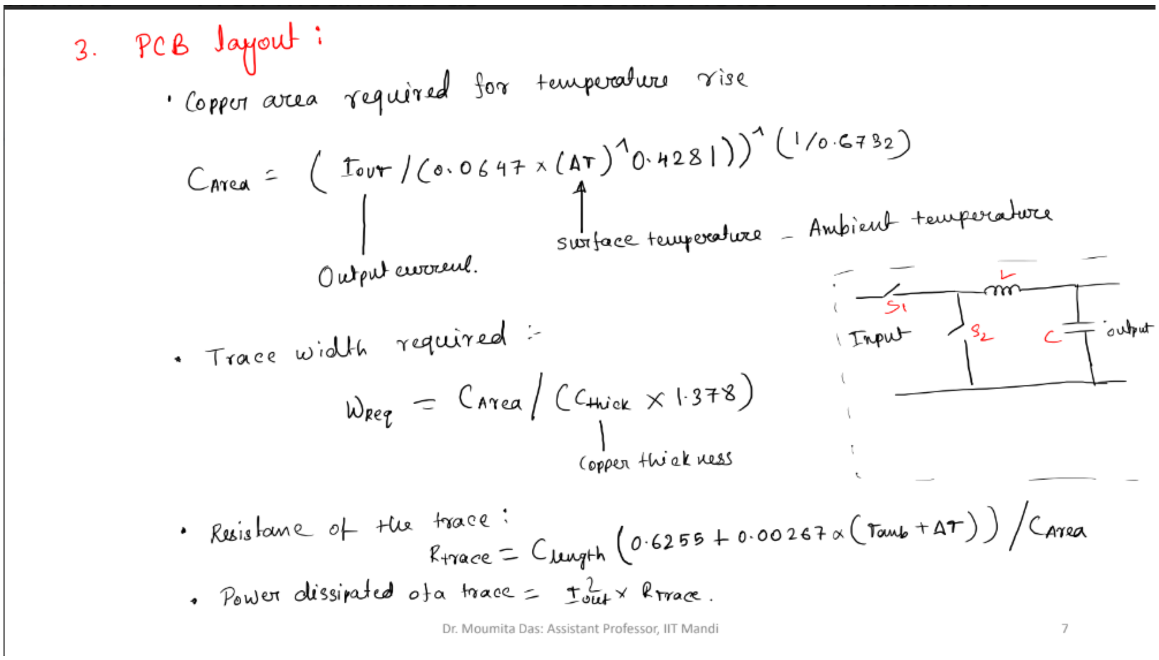

Right. So how PCB is designed that affect this power density in a greater way. Basically major portion like whatever losses we are calculating that is ok. But PCB plays very important role. So if I tell you about this PCB. So basically there is generally the copper is used for the layout. the PCB so the copper area required for temperature rise Can be calculated as copper area can be calculated as C area which can be given as I out divided by 0.

0647 multiplied by delta T to the power 0.4281. This bracket will close. Another bracket will close to the power 1 by 0.

6732. Okay. Now this is this delta T. It is surface temperature minus ambient temperature. okay and this i out is the output current this is copper area required now trace width in the pcb trace width required for heat dissipation for temperature rise it is We can require width required. So, basically this is width of the trace. It is C area that is copper area divided by

C thickness, copper thickness in the trace multiplied by 1.

378. So, this is copper area divided by copper thickness. This is actually copper thickness. okay so this will give you the required trace width so area of the PCB it's a copper area in the PCB and the width of the trace that can be calculated in this way from the PCB layout so that heat can be like heat rise in the temperature like in the PCB it can be taken care of so now this is resistance of the trace can be also calculated resistance of the trace whenever we have any trace any length any wire there will be resistance associated with it so now our trace length so basically W or I can just write down C length, copper length, length of that particular line in the PCB like any connection whatever we are considering multiplied by 0.6255 plus 0.

00267 multiplied by T ambient plus delta T divided by C area. Okay. Now this is resistance. Now power dissipated in a trace. So all this will ultimately give the power dissipated of a trace can be I out square multiplied by r trace. So, this is how we can actually calculate length, width, area of the copper in the PCB. So, basically in any converter, so if you see now just this, I will just use this particular So any converter if I consider so this converter let's say this is synchronous buck converter.

This is having inductor and the capacitor. So generally capacitor can be at the input and output. So input I am just using input source and output. so you can see here this this magnetics related losses inductor related losses capacitor related losses and then switch and diode i did not discuss in details in the last class i have discussed today i haven't discussed so again like if it instead of s1 and s2 if you use diode in place of s2 so there the loss will be different so that way you can again optimize that losses in the semiconductor devices or active component passive component you know how to select this all this thing again like After selection how you are actually making PCB that plays very important role. So that is why PCB design is very important and how we can use the layout for optimize the system size and then also reduce the losses or increase the efficiency that is actually very important area.

or the important part in this particular subject. So, that I will discuss next. So, for reference you can use on semiconductor application note. So, you can get all the calculation everything from there. So, that is it for today. Thank you.