**Power Electronics and Distributed Generation**
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**Lecture - 32**
**Thermal Model, Management and Cycling Failure of IGBT Modules**

Welcome to class 32 in topics in Power Electronics and Distributed Generation, we have been discussing the selection of a power semiconductor components.

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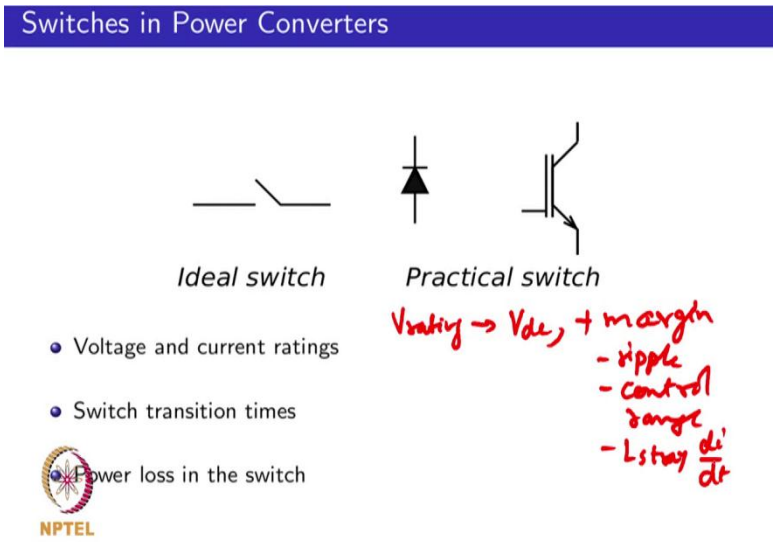


We have been talking about the voltage rating and the current rating, etcetera, so we saw that voltage rating of a practical semiconductor has to be selected based on your d c bus voltage, you might have some margin. And you need margin, because of your ripple in your d c bus, then be rippled you might have a control range, because if your would have, a step response, it might have an over shoot, you might have also L d i by d t effects, because of the stray inductance.

So, for selection of your voltage rating of your semiconductor, you need to incorporate the appropriate margin. So, then we also looked at the current rating of a device and we saw that the current rating is linked to the temperature rise; and to evaluate temperature rise one should look at the power loss in the semiconductor quite closely.

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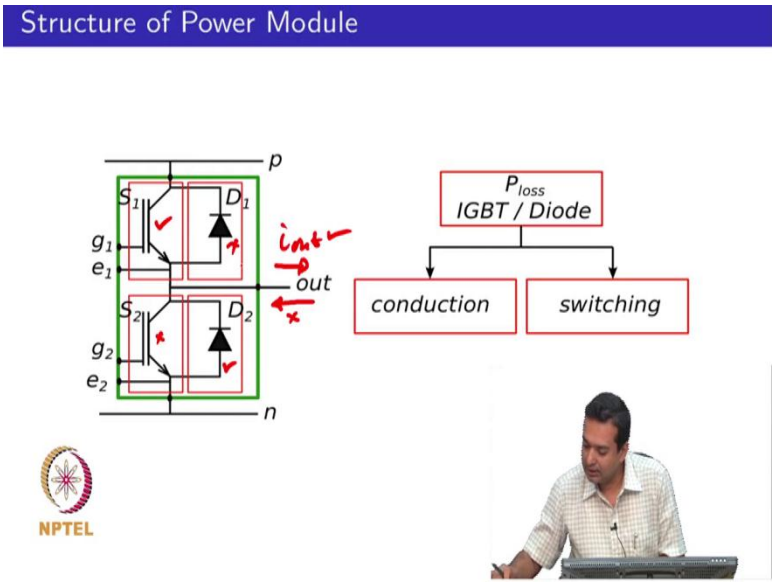


So, we looked at a the conduction loss, it is important to evaluate the conduction loss, the switching loss these are the major components in low voltage a systems and one need to evaluate this separately for both diodes, frivoling diodes IGB, the transistors within the module package. So, once you look at the losses, you have we also saw that the losses in the individual chip, depends on the polarity of the current, because in this particular structure if the current polarity is flowing out.

If the i out is positive, then essentially your transistor S 1 and diode D 2 would be the devices that are conducting, if the polarity of the current is in the opposite direction, then essentially it would be switch S 2 and D 1 that conducts. So, you have to look at not just the total number of devices you will have to look at, when each devices carrying current and when there is conduction loss and when there would be switching loss in a particular device.

So, one can write the expressions for the switching loss and if you evaluate the switching loss for say one set of transistors, one diode say corresponding to say S 1 and D 1, then the losses in the other transistor and diode would be similar. Because, of the symmetry in your modulation and also the symmetry in the current wave forms, that flow through the a c output.

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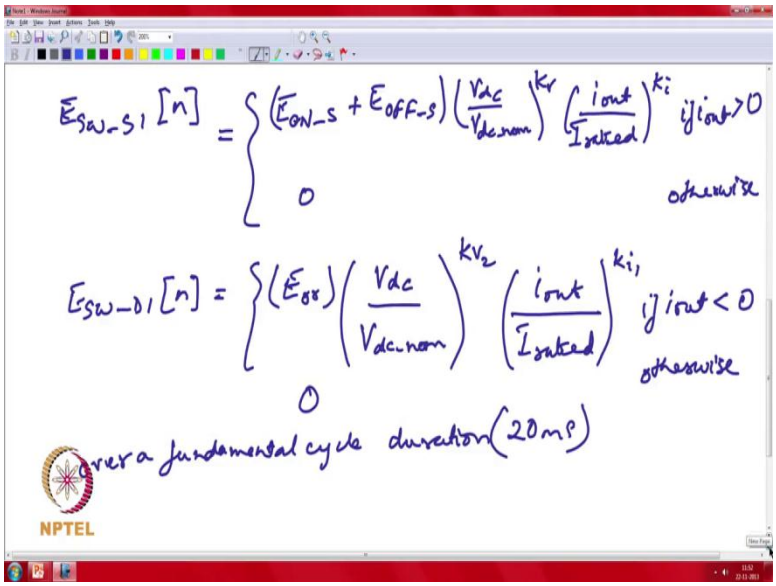


So, you can write at the expression for E s 1, switching loss in switch S 1 and we can consider it over n instance, and the n would correspond to each individual switching cycles. So, suppose you are switching at 10 kilo Hertz your switching period is 100 micro seconds, your fundamental might be 20 milliseconds, so you might have 200 points over which you can evaluate your switching loss and your conduction loss over the fundamental period.

So, you can write the expression for E s w of n as E on of S into V d c by V d c nom or k v, if i out is hostile and it would be 0 otherwise, similarly you can write the expression for the switching loss and the diode D 1 over the instance. So, this would typically be due to the reverse recovery effects in the diode and you have again scaling for you actual voltage V d c by V d c nom, note that your V d c by V d c nom would not change significantly over the operation of the inverter.

Say if you are operating if your V d c nom is specified at some voltage might be 900 volts or 1000 volts V d c actual might be 800 volts, but your actual operating range of the inverter would be a small range around the 800 volts it would not be a large range. So, this might be say another factor k v 2, but your i out is something that is varying over a much wider range, it is varying from a positive value going to 0, going to the positive the through the positive peak.

So, this is something that is actually varying quite a bit, as you are going along you are your fundamental cycle, whereas your V d c is actually comparatively a constant number, which does not vary as much as your i out term. So, you would have losses in diode D 1, when i out is negative or 0 otherwise, so over a fundamental cycle, so we are talking about 20 milliseconds for 50 Hertz, we can then evaluate the switching loss over the duration.

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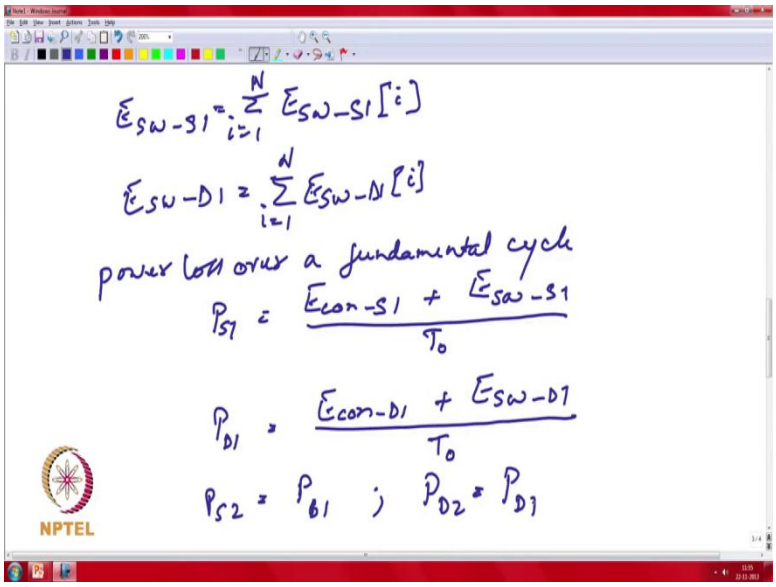


The total switching loss E switching loss in switch S 1 is summation i is equal to 1 to capital N, so if you talking of 10 kilo Hertz and 20 milliseconds your capital N would be 200 points. So, your power loss over a fundamental cycle can be, then calculated as P S 1 is your conduction loss term in switch plus your switching loss term divided by the period over which you were calculating, your fundamental period T naught and P D 1 is E conduction loss in the diode D 1 and switching loss in D 1 over again the fundamental period.

It is possible instead of doing this summation for sinusoidal wave forms with assumptions that you are k i is equal to 1, then it is possible to obtain close form expressions for the conduction loss switching loss. But, doing this calculation is not going to be overly complicated, because your summing over 200 points which is not too large, in terms of the total number of points that which you can evaluate, you can easily

do that on a your spread sheet, you do not need any sophisticated, very sophisticated tools to evaluate it.

Also this general expression can be used for a more complex wave forms, that might flow when you are having say for example, in active filter where you do not just have fundamental current going out, but also you have harmonics and other forms of current wave forms. Your power loss in your switch S 2 by symmetry is taken to be equal to P S 1 and power loss in D 2 again is taken as power loss in D 1, so once you have the power loss in S 1, S 2, D 1 and D 2, you could then use it to evaluate.

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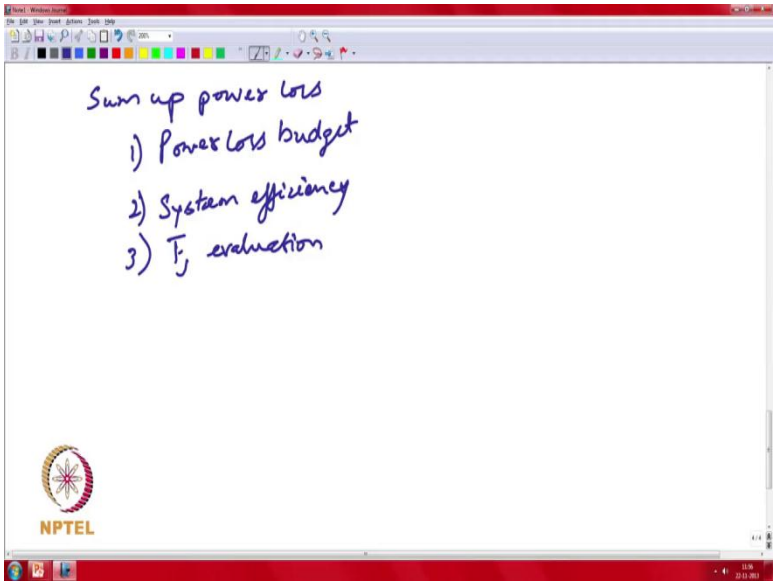


You could for example, you can look at what your loss budget of your inverter is, you could look at your system efficiency, so if you include the other terms for the balance of components, the loss in your d c bus, loss in your filters. Then sum it with your semiconductor losses you could evaluate your system efficiency, you could then look at your thermal limit, your junction temperature evaluation, so evaluating the power loss is important from multiple factors.

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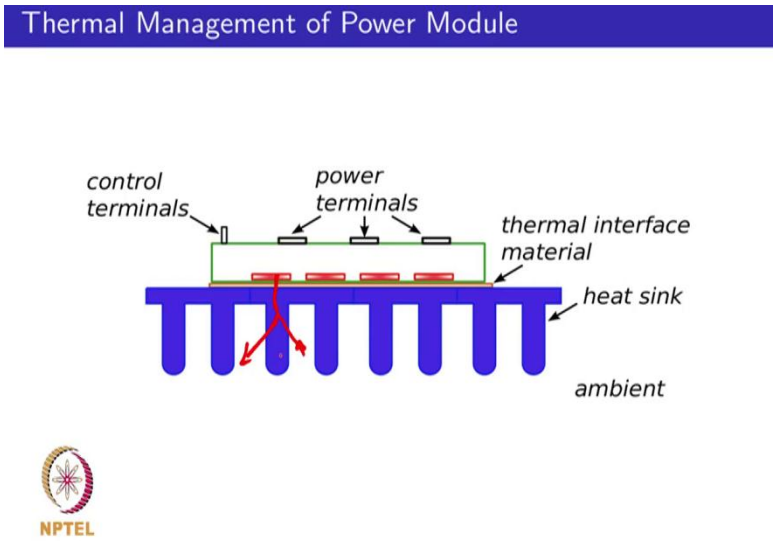


So, once you one and one of the critical aspect to your factor is to actually look at the junction temperature evaluation, because your actual operating limit of how much current you can pass through your inverter is actually limited by your T j limit. So, to obtain the thermal limit, you have to look at how the overall thermal management of a power module is done and you have power dissipation happening in the individual chips say your four chips are shown; but there can be dozens of chips within a single module.

And if you look at the heat flow heat flow path in a typical module, the heat flow is from the chip down into the base plate of the module, below the base plate is a heat sink and you typically have thermal interface material, thermal grease, which is used to ensure that you do not have air voids between the base plate and your heat sink. Because, air voids act as a insulators, thermal insulators you want to avoid the voids, also even with tight tolerance on the surface finishing of your heat sink and your base plate, there will be still be some curvatures.

You want to ensure that there is good contact, especially when you are tightening the screws on the edges to mount the module on the heat sink, that curvatures would change and you need to ensure that you are having a some thermal contact, all across from your base plate to your heat sink. Typically the thermal resistance of the thermal interface material can actually be quite appreciable, even though the layer thickness is quite small it is typically of the order of tens of a micro meters, it is not a thick layer.

But, even that finite layer can actually introduce thermal resistance between your chips and between your base plate and your heat sink. So, essentially your heat flow path is from your chip, down into your heat sink and out through from your heat sink to your ambient and between your chip and the base plate, you would have additional layers will look at those layers in detail.

One thing that you want to do is, you want your chips, which are actually carrying the electrical potential to be isolated from your heat sink. So, there is a ceramic layer typically aluminum oxide or aluminum nitride commonly used, so there is a ceramic layer, so from there it goes to the copper layer, then through the thermal grease it goes to the sink. And then, the heat sink is typically aluminum is common material, you might have other materials of special heat sinks and out to the ambient. Again ambient is typically air, it can be forced air natural air cooling can also be water, oil, different materials, there can be other specialized thermal management structures too, but commonly it is air.

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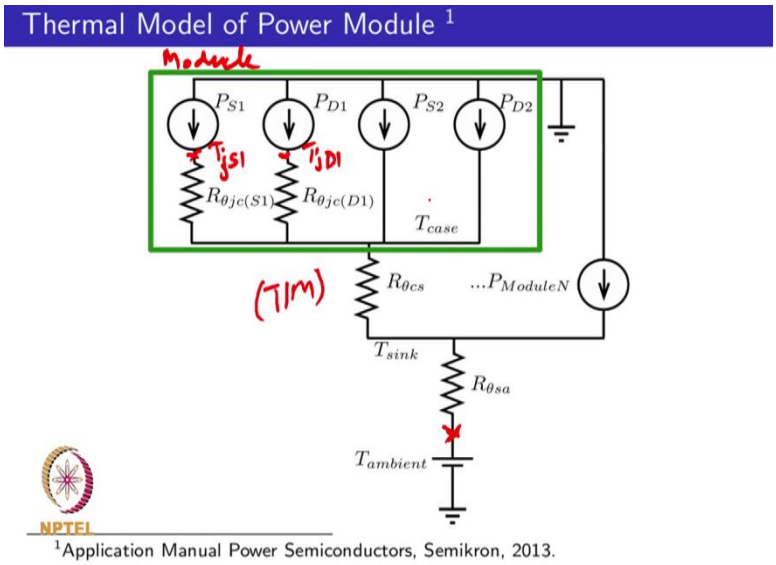


So, to look at the overall thermal junction temperature, one has one should actually look at evaluate the structure and look at how to generate a thermal model of your overall system.

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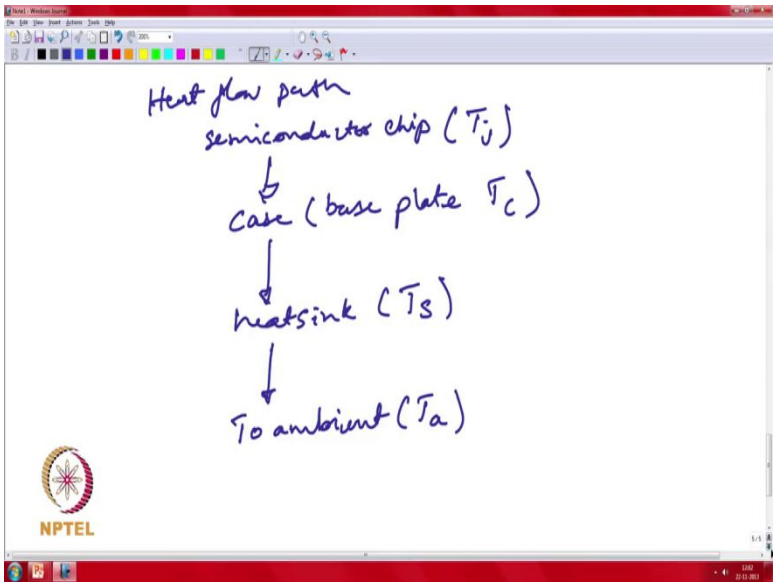


So, to do that, so this is where you evaluate the virtual junction temperature, then you have a dominant point where loss of interest is your case, the case temperature in our case is consists of your base plate, base plate temperature. And from your case you are going to your sink and from there, you have your thermal impedance going the it could be the actual conduction through the aluminum structure; and also a dominant term would be the interface from your surface of your aluminum finch out into the air. So, this is your heat sink temperature and this is your ambient temperature, so if you look at the thermal model of such a structure, one common method of analyzing the thermal the structure would be to do a equivalent electrical circuit.

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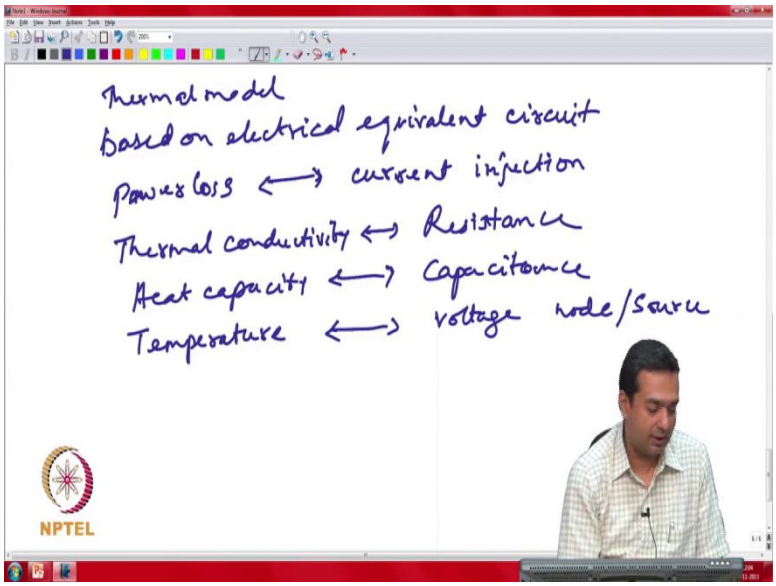


And your power loss is considered a current injection, so it is a current source in your electrical equivalent circuit, your thermal conductivity of your structure, of your thermal system is model using thermal resistance as the resistance. And your heat capacity if the object that your are studying is looked at as a equivalent capacitance, and that actual temperature is modeled as the voltage of a node or of as a voltage source.

So, if you look at the steady state model of thermal circuit of your ((Refer Time: 20:13)) IGBT and your heat sink, there are multiple factors that one would need to consider. So, because you are looking at a steady state model, you are modeling essentially now with current sources, voltage sources and just resistors. And the factors that you would need to consider a if you looking at say module 1, a single module shown within the green boundary, then you have to look at what are all the possible power losses in this case, we are looking at two level inverter, there is power loss in switch S 1, S 2, diode 1 and diode 2.

If there are more complex structures you will have to look at the total loss within a single module, you might have modules with multiple legs, you might have more complicated topologies such as multi level power converters. So, the first thing is to consider all the laws that aggregates in to a single module and here, we are considering your power loss in switch 1 to be equal to power loss in switch 2. And because of the symmetry of

operation, we are looking at a your junction temperature of your switch 1 to be equal to the junction temperature of switch 2.

So, you do not have to explicitly evaluate the junction temperature of switch 2 by adding a resistance over here, because current source in series with the resistance would still inject the same level of current, into the case of your module. So, you can evaluate your T j of your switch S 1 and here you can evaluate T j of your diode D 1, similarly if you have multiple modules that are mounted on the heat sink here, what is shown over here is the is the thermal resistance between your case and the heat sink.

So, this would correspond to your thermal interface material, which is the thermal grease, so if you have multiple modules now mounted on a single heat sink, then you can put multiple equivalent current sources. So, a second module would be modeled by a current source whose value would be equal to the some P S 1 plus P D 1 plus P S 2 plus P D 2. So, depending on how many modules you are mounting on the heat sink, you can add addition current sources.

And assuming that all the modules are operating in a symmetric manner, suppose you have a 3 phase system, you would be operating your phase R Y and B in a symmetric manner and you would also assuming that the maximum loading on R Y and B, in terms of the current loading is similar. So, you do not need to again explicitly evaluate the junction temperatures of your phase Y and B, you can use the same value that you obtain from T j S 1 and T j D 1.

Here, then once you have all the modules on a heat sink will have to look at the temperature between the heat sink and the ambient, you can also have converters which are where the modules are mounted on multiple heat sinks, in which case you would have multiple branches to indicate the sink to ambient temperature; so in case you have multiple heat sinks within a single cabinet. One thing to know to over here is that, we are considering the ambient temperature over here, in a power converter your ambient temperature, in this temperature might correspond to temperature within a cabinet.

If you have the external air that is being specified to you, you will then have to evaluate what is the thermal exchange between your cabinet internal air and your external air, which would give you additional voltage drop between your internal and external. So, you need to know where exactly your ambient is being reference to, whether is the

external air or internal air, if it is the internal air in the cabinet, you will have to look at not just the losses in your symmetry conductors.

You will have to look at the losses that are coming in from your other components, there might be fans within the cabinet, which are dissipating power there might be inductors, filters, a wide range of structures, which would make your problem. Lot more complex and not and not essentially a asymmetric as evaluating a single semiconductor structure on a heat sink.

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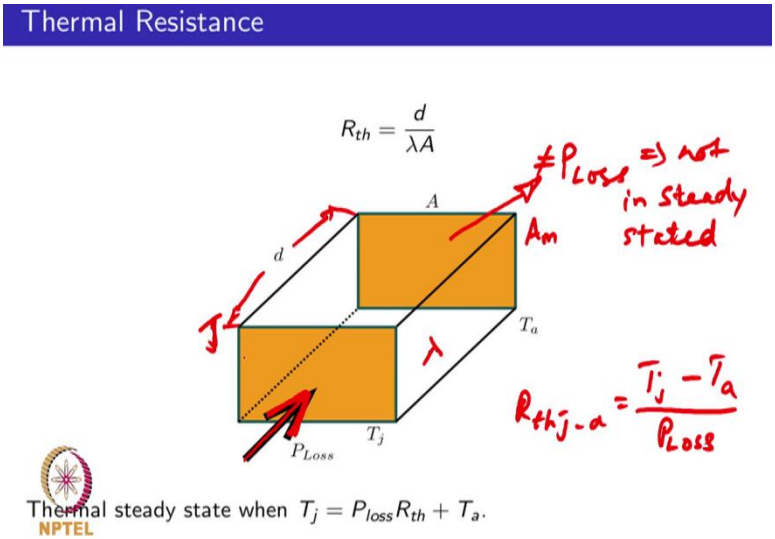


So, if you look at the thermal structure more closely, your thermal resistance essentially is a proportionality constant between the surface, the temperature difference of two surfaces. In this case say will call it surface J and surface A or will call it A m, the A m represents say the surface of ambient temperature and surface J represents the surface corresponding to say the junction temperature.

And so your thermal resistance is the proportionality constant between how much, what would be the temperature difference between these two surfaces. We will consider these surfaces to be a constant temperature, and what is the power flow that is going between the two surface under steady state conditions. So, if you consider a object say a material of thermal conductivity lambda and say the distance between the surfaces d and we are considering a cuboidal structure and say the cross sectional area, from surface J to A m is A.

Then you can evaluate your thermal resistance as d proportional to the distance, inversely proportional to the thermal conductivity and inversely proportional to the cross sectional area. Similar to the resistance electrical resistance of a material of electrical conductivity that is specified T a. So, in case your power loss in the switch that is going in into your surface J is equal to the power loss that is coming out of your surface A m, then you say that this particular system is in thermal steady state.

Suppose, your power injection into the surface J is higher than the power that is coming out, so if it is not equal to P loss implies not in steady state. So, the proportionality the definition of the thermal resistance R t h from say junction to ambient is defined as T j minus T a under steady state conditions divided by power loss. So, initially if you look at these two surfaces, before you have any loss initially both surfaces J and A m might be at the same temperature, when you just apply a step say power loss into surface J, the initial temperature of the surface J would be equal to the temperature of the surface A m.

So, as time proceeds the temperature of a surface J is going to increase from your ambient T a to a elevated value, which finally settles down at T j, so initially your power loss that is coming into J, would not be equal to the power loss that is going out of J. And because, your power loss or your heat flow in surface J is now more, that energy is being stored somewhere and it is being stored in the heat capacity of the material.

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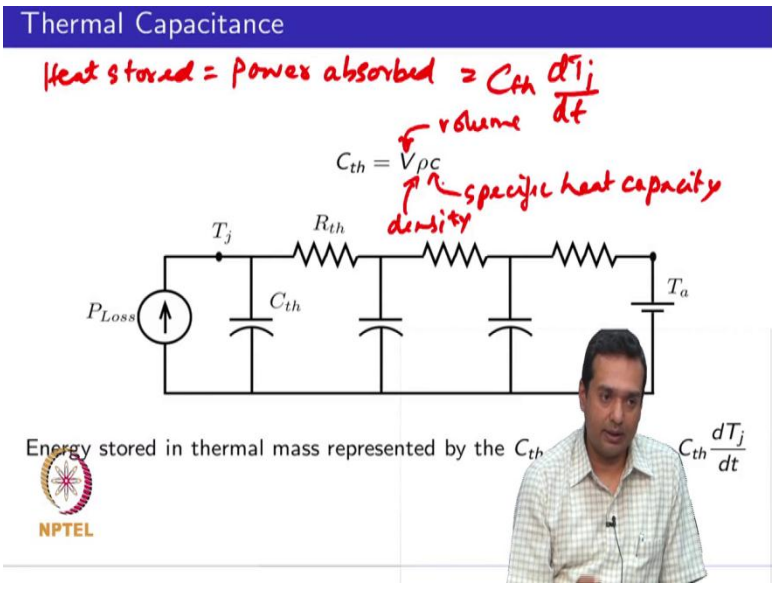

So, you can look at what is the power absorbed in say an object and you can write an expression your heat stored would be equal to power absorbed by the material, and your power absorbed is given by your thermal capacitance into d T j by d t. So, essentially your thermal capacitance represents, thermal storage in your electrical capacitance would represent charge storage, so it is equivalent of that when you are looking at it from a electrical perspective.

So, if you are specifying the heat capacities specific heat capacity of the material, say c is the specific heat, V is the volume of the material and rho is the density. Then you can write an expression for your thermal capacitance to be essentially your mass, times your specific heat capacity to give your thermal capacitance of your material and again the nodes of interest. So, you can write simplified expressions for your c T h for different items that is being considered in your module.

So, in your module if you are considering different sections, you could look at what is the thermal resistance in a simplified manner, you could also consider the heat capacity of objects. We mentioned that the thermal interface layer is extremely small only microns thick, so there is not much heat being stored within your thermal interface material is just a temperature raise. So, whereas, you would have a lot of material and your heat sinks, so there can be potentially a lot of storage in your heat sink, comparatively a smaller amount in your base plate.

Because, it is typically smaller in size than your heat sink your energy stored in your semiconductors would be still smaller. And again your temperatures of interest or your virtual junction temperature T j, your case temperature, your heat sink temperature and the ambient temperature. In the real physical structure they are many more intermediate nodes in the thermal structure, but you may not be interested in all the intermediate nodes in interested in the major nodes, that can be readily observed.

So, if you look at such a structure of capacitance and the thermal resistance, this corresponds to a physical model of your heat flow within your structure of your thermal management structure. So, if you look at the thermal system, you could then define a thermal impedance rather than just a thermal resistance, when you are looking at a dynamic model of a thermal system. And essentially you are looking at how your

junction temperature would not just a behave, what value it would have in a steady state, but on a dynamic bases.

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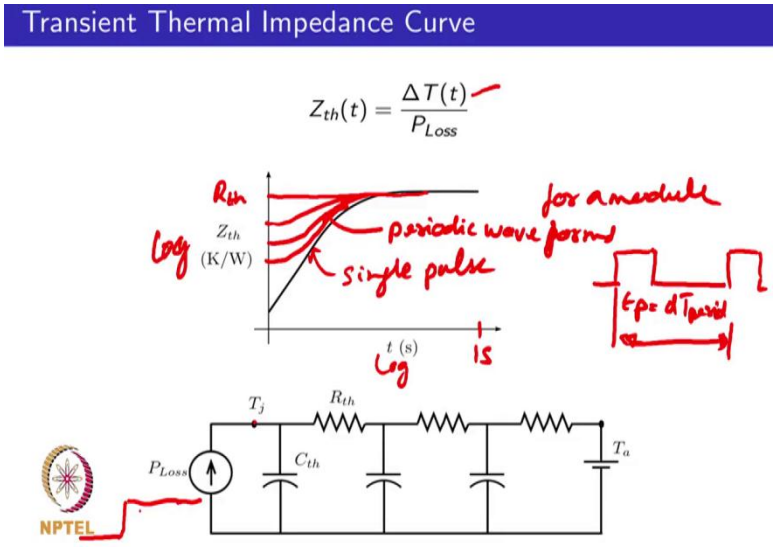


Also the transient thermal impedance curve is something that is provided in the data sheet, so you a typical transient thermal impedance curve would be a curve that is plotted on a log log bases. So, you are talking about a longer time frames of the order of a 1 second for a power module, whereas at a extremely small values of time of the order of micro seconds to milliseconds, your transient thermal impedance would have a very small value.

And your steady state value over here would correspond to your R t h, R t h on a steady state bases, so this curve what is shown over here is for a single pulse, which what essentially you mean by a single pulse is your power loss is essentially a step. And there is only one step going on forever and essentially your definition of your transient thermal impedance, is essentially the step response of your junction temperature when for a given step in power loss. Your delta T in this particular case, when you are looking at the transient thermal impedance of a module is T j.

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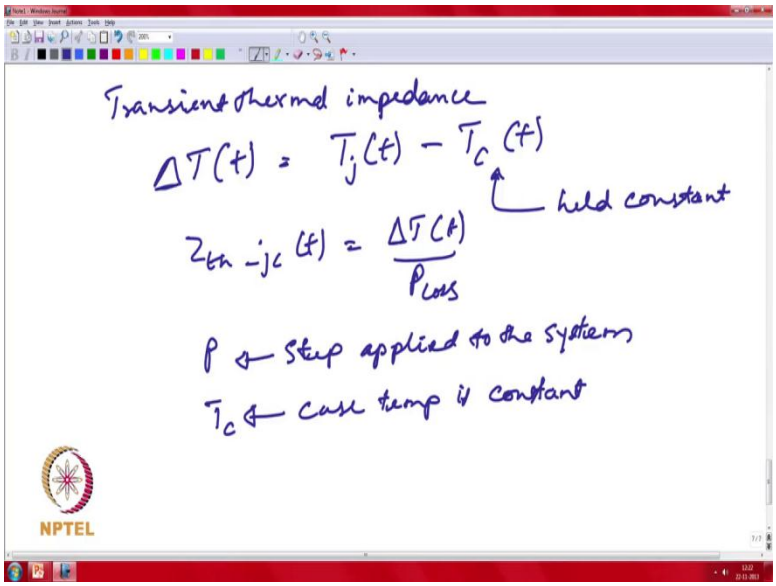


So, your delta T is a function of time and essentially it is T j of t minus T case of t and often when your measuring your transient thermal impedance of a module, your T case is being held at some specified temperature. So, you might have a active thermal loop ensuring that your case temperature is held constant that some value may be 25 degree centigrade and then, your essentially looking at how your junction temperature, what is the rise of the junction temperature over your case temperature.

So, for extremely narrow pulses for very short duration, all the energy that is flowing into your junction surface is just going into as stored energy to raise the temperature of the chip, so you will not see an immediate step increase in junction temperature. So, because of the storage effect you would start from a small value and gradually increase to a steady state value as time proceeds. So, your Z t h of your junction to case as a function of time is your delta T of t divided by your P loss, so here there are couple of assumptions one is that P is a step.

So, for example, one could apply a step current and we know that the power loss due to the step current, because of V c on would have a similar step nature and then, you could consider use that power loss. And then, evaluate what your resulting temperature is that you are on state voltage varies to some extent with temperature, and measuring the on state voltage you can actually calculate back what your actual temperature is. So, the

second assumption is your case temperature is constant, so this can be with a thermal path some active cooling to ensure that your case temperature is being held constant.

Manufacturers also provide your transient thermal impedance for different duty cycles also ((Refer Time: 38:13)), these curves are provided say for duty cycles, for periodic wave forms. So, essentially instead of having a step wave form in this case, you are having a duty cycle and a period in which your power is being dissipated; and essentially the square pulse is being repeated and your t p is essentially some duty cycle times your overall period T over which this is being considered.

So, if your duty cycle is extremely small and your period is long, you will have transient thermal impedance curves which are coming for the down, if your duty cycle is high and your periods are extremely small. Then essentially, you will get a transient thermal impedance curve that looks like this, often the power dissipation in a practical power converter may not be periodic step wave forms, it might be more dynamic than just the step it might be...

So, one would need to evaluate the, what the actual junction temperature is when your power loss is a more general form rather than just a single step or periodic wave form, periodic pulse wave form. So, if you look at in a DG system, you have many situations where you have such a dynamic power variation, power loss variation for example, if you have a wind turbine the power wind speeds are varying with time.

So, your operating power level is varying with time, which means your classes are varying with time, if you are having same thing with a solar converter you have clouds moving, you have shadows going across your panels, so your power level is varying. You might have distributed generation system, which are connected to loads and the loads themselves are varying do not know when the load will be turned on or a load would be shut off; so to evaluate your power loss in a dynamic bases is also a important aspect.

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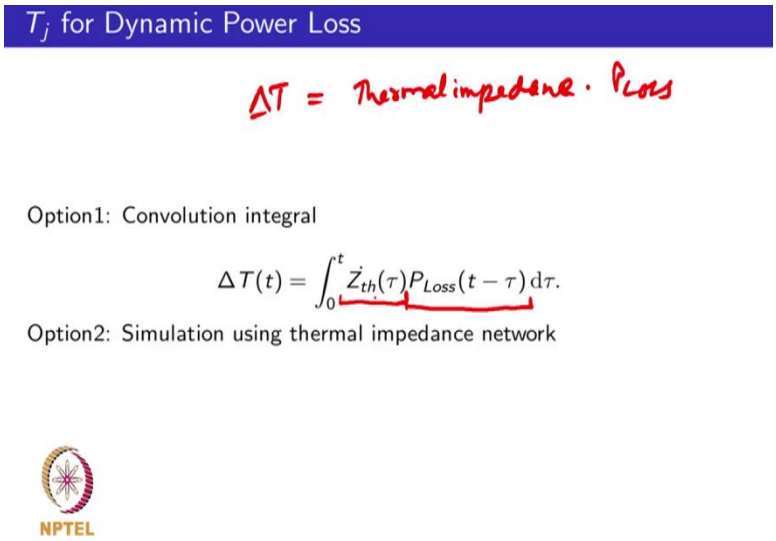


So, one way in which one can evaluate your temperature is to look at your expression we know that your delta T is essentially product of your thermal impedance, times your power loss, but here thermal impedance provided by the manufacturers not a impels responses, actually a step response. So, the data that you have from a manufacturer does not correspond to applying a impels of power loss and looking at what temperature would be as a function of time is actually a step response and what would be the temperature as a function of time.

So, you cannot directly the Z t h of t directly, but you will have to look at essentially your Z t h dot which is actually not been provided by the manufacturer. So, if you have the information of what Z t h dot of t of as a function of time, then you could apply a convolution integral to evaluate what your temperature raises and because, this is not a free available information this may not be directly applicable.

So, the next way in which one can easily evaluate your delta T is to evaluate the thermal network ((Refer Time: 42:37)), based on your Z t h of t evaluate a thermal network such as what is shown over here at the bottom of the figure. And use that particular thermal impedance in a time domain simulation to look at what your response of your system would be as a function of time.

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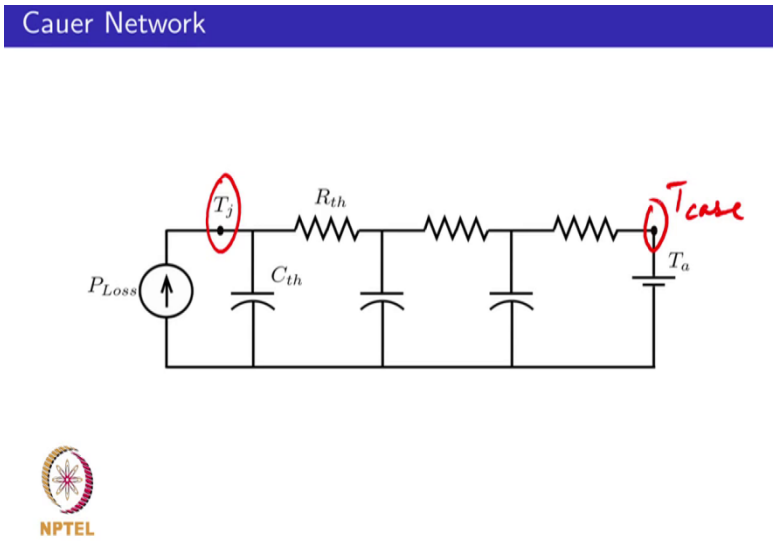


So, to do such a thermal simulation, there are two approaches, one is the physical thermal model that we had just discussed, consisting of a ladder network of R C elements; and your items of interest might be your junction temperature, you might have your case, your synch, your ambient. And one can actually this type of network is called a Cauer network and if you look at the intermediate points you might have, if you are looking at just a module in case it is a module that is being looked at this might be a case temperature.

And your in intermediate points you might have solder layers below chips, you might have the top of the chip, you might have isolation ceramics between your chips and your packaging, you might have the base plate, the upper layer lower layer of the base plates. So, you might have a number of intermediate layers, but again the items of interest are essentially T j and your T case, second way of evaluating your dynamic thermal model is with a Foster network.

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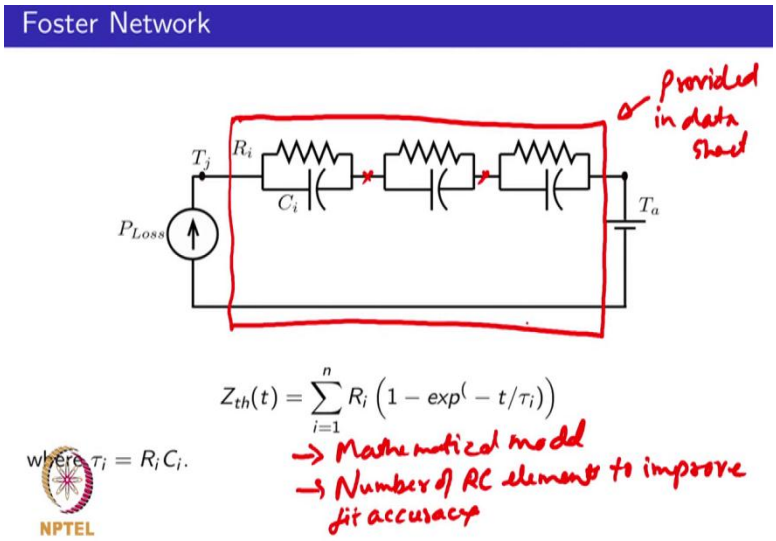


So, Foster network is essentially a series connection of R C elements, so again if you look at it from a overall perspective, if one end of ambient or at the case and one end is at the junction. If you consider this particular network to be a black box, from your terminal perspective it does not make a difference, whether you are using a the Foster network or a Cauer network, from a terminal perspective it is equivalent.

So, if you look at a Foster network you would have essentially expressions which is of the form, Z t h as a function of time is a summation over R C time constant. So, you can express it as R i into 1 minus exponential minus t by tau i, so if you look at such a model and if you want to then look at what are the intermediate voltages over here, these intermediate voltages have no physical meaning.

Whereas, if you looked at your physical Cauer model of your network, those intermediate nodes might have physical meaning of some intermediate surface, whereas this is just a curve fit, which ensures matching of your terminal quantities and the intermediate quantities does not have any physical meaning. You could also depending on the curve of your measured transient thermal impedance, you could increase the number of R C elements to improve the accuracy of the match of this particular network model and your actual measure transient thermal impedance.

So, this is just a mathematical model, which curve fit which tries to match, the response of this network with your measured temperature as a function of time, when you apply a

pulsed power loss into your semiconductor devices. And the other thing that you could do is increase the number of R C elements, improve the fit accuracy, if you look at the data provided by manufacturers they would have 2 to 6 R C elements in that are provided in manufacturers that provide this level of information, they would provide between say 2 to 6 time constants equivalently R C elements.

So, one thing is that if you take the Foster network, it does not convey any internal information of what the module is doing, it just gives you the items of interest T u which are the terminal quantities. And this is the information that is provided your Cauer network is not provided in your data sheet, so you can see that one difference of between your Cauer network over here is that all your thermal capacitances are to ground.

Whereas, in your in the Foster network all your only one capacitor at that last capacitor is connected to the ground, all the other capacitors are actually between terminals. So, one of the drawbacks of the thermal the Foster network is that it assumes that this particular node, in case you are looking at a module, then you are looking at this particular node as a case temperature ((Refer Time: 48:57)). So, it assumes T c and it does not assume that what goes beyond T c is actually a thermal impedance, assumes that it is a fixed voltage source.

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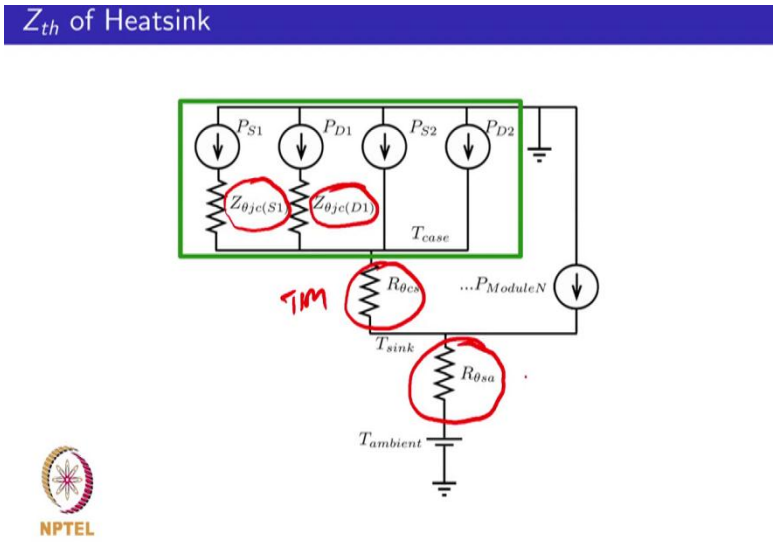


So, if you physically connect a Foster network model, for your thermal impedances within your module, two at the balance of structure you might have a thermal resistance

of your heat sink. And you might have the thermal resistance of your thermal interface material and your thermal resistance from your sink to ambient, if you do that for say a Foster network, what it means is that you have this particular model and it is being connected through your resistor.

And if you apply a step change over here, then the response would also see a immediate step, but we know that physically within a network, thermal network you will not see instantaneous jump in temperature, you have to have thermal storage before the temperature actually can raise. So, you cannot connect a Foster network to the balance of your structure, you have to actually transform it back to a Cauer network before you connect it to the balance of your thermal system.

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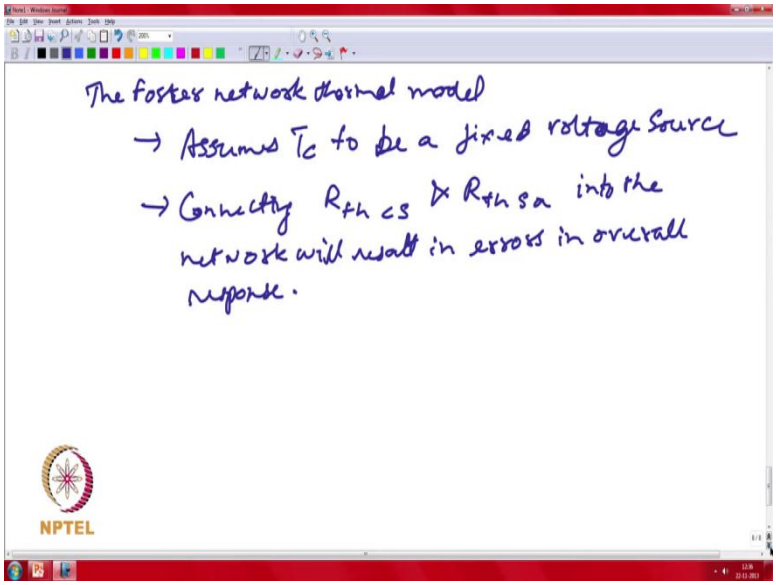


So, if you want to connect a heat sink to the thermal management network, you have to convert your foster network to the Cauer form. And if you look at the steps involved in, then evaluating the dynamic thermal model to a step thermal power load coming in.

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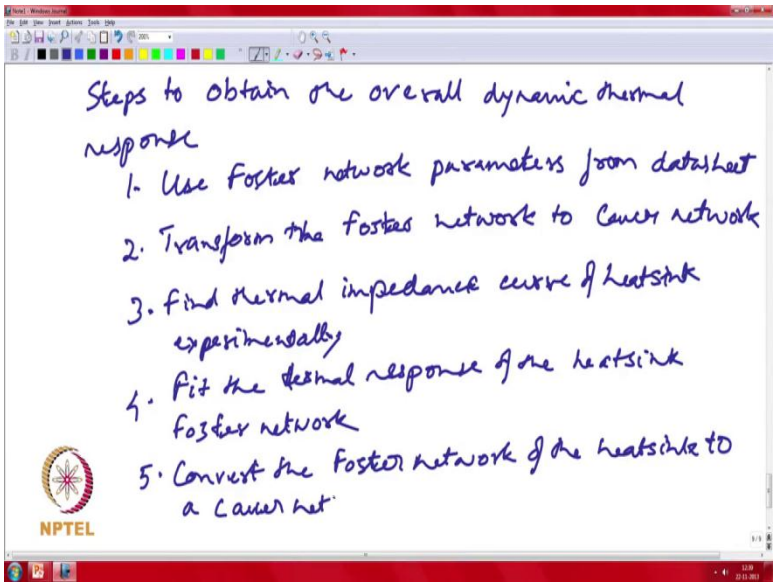


First thing is to use it to Foster network parameters, then you have to transform, could transform it to a Cauer network, your parameters for your modules are typically provided by the manufacturer. Typically you may not have much information about the heat sink, sometimes your heat sink manufacturer give you some information on thermal resistance, but you may not have a dynamic thermal model of the heat sink, so you will have to actually determine it experimentally.

So, the next thing that you do is from your measure data, it is easier to fix R C time constants into your step response, so you can obtain the fit the thermal response to obtain the heat sink Foster network. The next step would be to convert your Foster network of your heat sink again into a Cauer network, so after that you connect your thermal networks together, because once you have it in Cauer form you will be able to do that.

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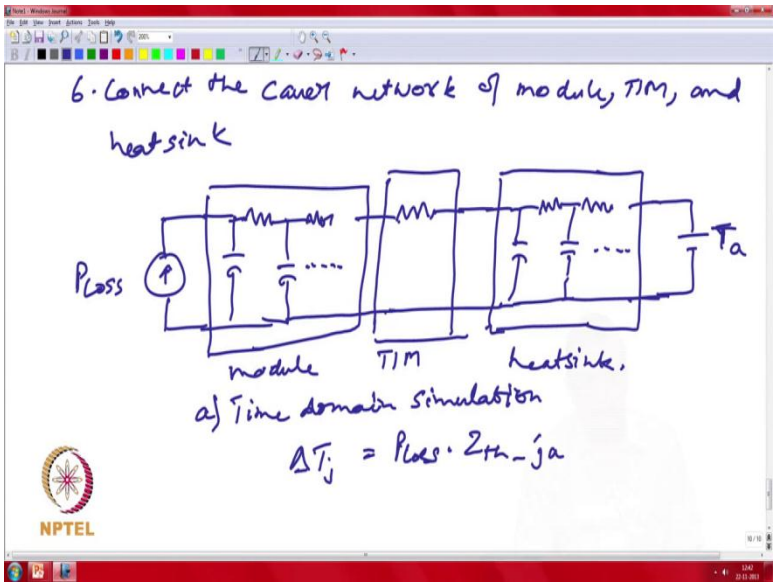


The thermal interface and heat sink, so essentially you have your power loss as your source, you would have a network models for your module, which would be in R C form you might have just a resistor modeling your thermal interface material. You might then have another Cauer network representing your heat sink going out to your ambient which is essentially specified by your requirement, what temperature your system is going to operate.

So, once you have the combined network for the module, your thermal interface and heat sink, you can then do either a couple of things, one is you can do a time domain simulation. Or you could combine the impedances of your overall network it is a long ladder network and you can then, calculate your overall delta T j to be your power loss times your Z t h, now for your junction to ambient, your combine impedance of your overall network in your appropriate time domain.

If appropriate frequency domain Laplace or looking at a explicit functions, depending on the type of dynamics you expect in your power loss. So, one thing that we have seen is that to do this overall things of a dynamic thermal module evaluation, you have to backend forth between Foster networks and Cauer networks. So, will take a look at what would be the type of analysis you would need to do such transformations in the next class.