Power Electronics and Distributed Generation
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Lecture - 33
Semiconductor Switch Design Reliability Considerations

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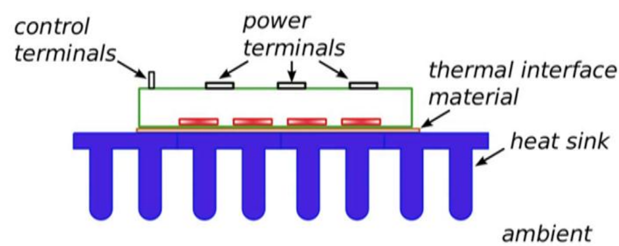
Thermal Management of Power Module



Welcome to class 33 in topics in Power Electronics and Distributed Generation. We have been looking at the dynamic thermal models of IGBT module and we have seen that it is important to evaluate the junction temperature of the semiconductor, chips, transistors, diodes, etcetera. And to do that we looked at concepts of thermal resistance, thermal capacitance, and how to module it as a equivalent electrical circuit.

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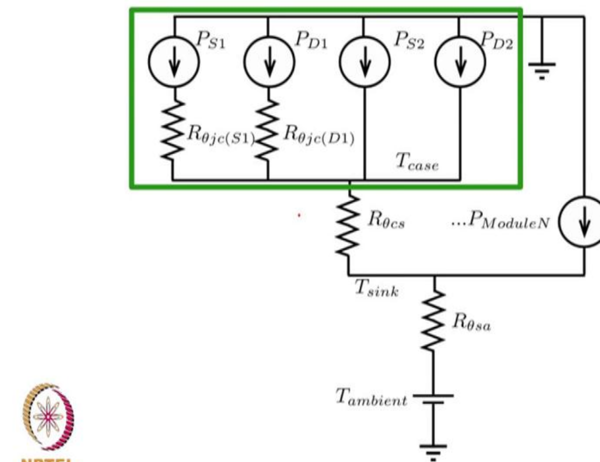
Thermal Model of Power Module [1]



[1] Application Manual Power Semiconductors, Semikron, 2013.

And we saw that the electrical circuit can be mapped to a network of to look at the steady state behavior of the of such a of the thermal management system, and to look at the dynamic thermal characteristics.

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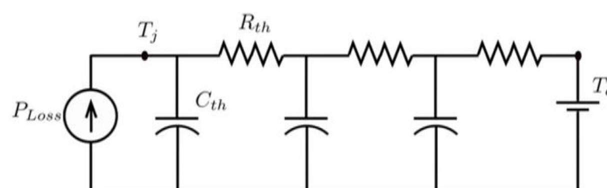
Cauer Network



One can then look at a ((Refer Time: 01:30)) network which looks like the physical R c networks that would correspond to the physical thermal characteristics of the multiple components that go into the IGBT module. The points of interest would essentially be your junction temperature, may be your case temperature, sink temperature or the

ambient. And often in a power module the case temperature the data sheets provide transient thermal impedance characteristics for a fixed case temperature, and you are looking at the transfer function between your junction temperature to case temperature.

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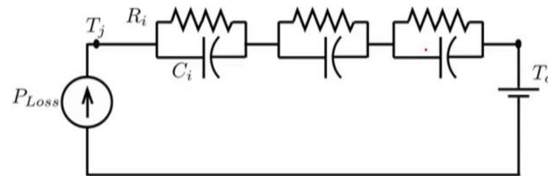
Foster Network



$$Z_{th}(t) = \sum_{i=1}^{n} R_i \left(1 - exp^{-t/\tau_i}\right)$$

where $\tau_i = R_i C_i$.

And the same behavior can be obtained from a equivalent foster network from again, from the junction temperature point of view. So, the intermediate nodes of the foster network may not make much physical sense, but from a terminal point of view the behavior of the Foster network is similar to that of the Cauer network.

The number of R c elements can be typically it is between 2 and 6 the number of elements can be higher to get a better approximation to the thermal response characteristics of your measure measurements with your model of the thermal system. The data sheets provide typically the Foster network parameters are a some data sheet might just provide the transient thermal impedance curve. And we saw that connecting the module together with the heat sink one has to make transformations between the foster and the Cauer networks.

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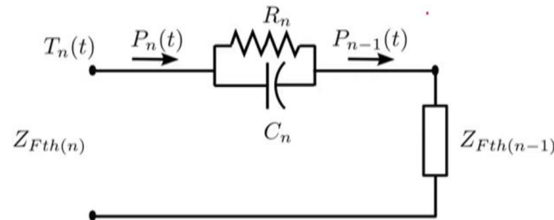
Foster Recursive Unit



So, if you want to analyze the Foster and Cauer network then one has to look at how the impedance can be evaluated for each of this, so will look at a foster network as a recursive unit.

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$$Z_{fth(n)} = \frac{1}{1/R_n + sC_n} + Z_{fth(n-1)}$$

$$= \frac{1/C_n}{s + 1/R_n C_n} + Z_{fth(n-1)}$$

Similarly

$$Z_{fth}(n-1) = \frac{1/C_{n-1}}{s + 1/R_{n-1} C_{n-1}} + Z_{fth}(n-2)$$

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And if you look at the impedance of the nth recursive unit of the Foster network Z f t h of your nth unit is 1 by R n plus S C n plus Z of the Foster network of the previous stage. So, if you are looking at it this is the impedance ((Refer Time: 04:10)) of the Foster network, subsequent to the nth unit and you are adding the nth component to it to get the

foster impedance at the nth stage. If you look at, so you can write this as 1 by C n divided by S plus 1 by R n C n plus Z f t h at n minus 1. So, in a similar manner we have Z f t h half n minus 1 can be written 1 by c n minus 1 by s plus by R n minus 1 c n minus 1 plus Z f t h of n minus 2.

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So, you could write general expression for the Foster network to be of the form within sections. So, if you look at the form of this expression this is essentially a partial fraction expansion of the transfer function, if you write Z f t h to be a ratio of polynomials P n of s by Q n of S. Then essentially it is the partial fraction expansion of such a polynomial, you could also then look at what is the ((Refer Time: 06:27)) recursive unit for a Cauer network. So, essentially you are looking at Z c t h at the nth stage in terms of the R n C n parameters and Z c t h of the n minus one stage.

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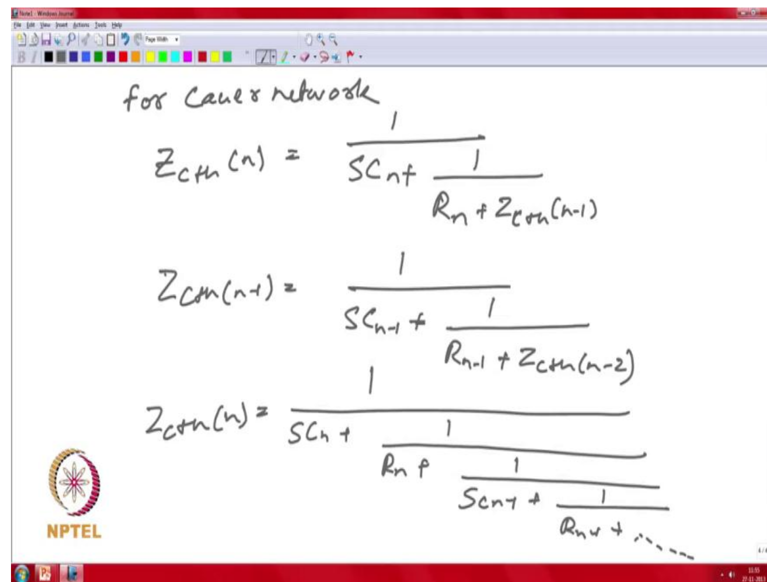

So, you have a capacitance in parallel with the resistance plus your subsequent network impedance. So, it is 1 by S C n plus R n plus Z c t h of n minus 1 and you can write Z c t h of n minus 1. So, if you look at the structure of the impedance the general expression for a Cauer network with n stages it can write Z c t h of n is 1 by S c n plus 1 by R n plus 1 by S C n minus 1 plus 1 by R n minus 1 plus essentially this would continue along. So, the structure of this is of the form a continuing fraction. So, if you have a impedance that is provided to you as a Foster network impedance and you would like to transform it to a Cauer network.

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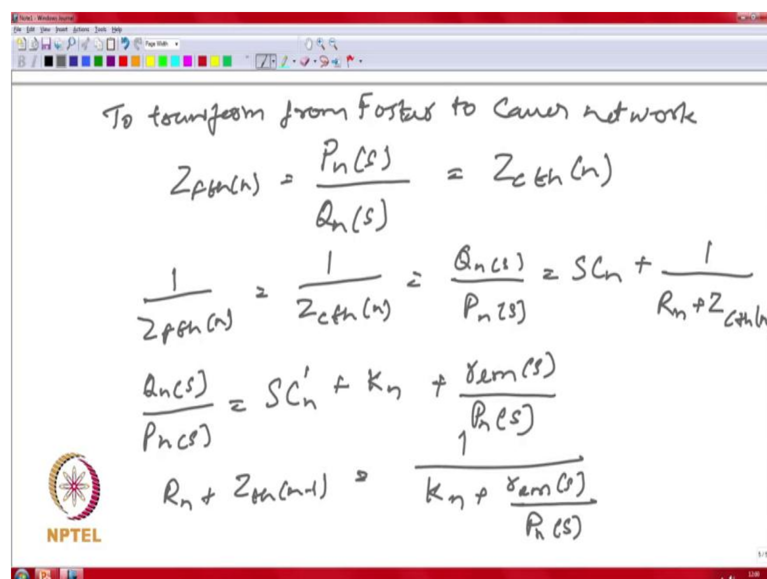

We let the foster network that is provided to you Z f t h of n be the ratio of polynomials P of n of s by Q n of s and for thermal systems you would have P n of S to be a polynomial of degree 1 less than the denominator polynomial Q n f s. So, we know that the foster to Cauer transformation the Cauer impedance would also be equal to the same ratio, so this is also equal to Z g t h of n. So, you could then evaluate your Cauer network one look at 1 by Z f t h of n which is 1 by Z g t h of n which is Q n of s by P n of s and because Q n is 1 degree higher than p n you can write it as some S C n, you can take the s outside plus 1 by R n plus Z t h.

So, essentially we have written this S C n plus one by r n plus z c t h from our structure of essentially the Cauer network which we know is of this particular form ((Refer Time: 11:03)). So, you could also now we know that Q n of n is 1 degree higher than P n, so you could apply a Euclid's long deviation for polynomials to get Q n of S by P n of S equal to S C n prime plus k n plus essentially the reminder of the deviation by e n of S now you the reminder of a the deviation to be 1 degree lower than the degree of P n of S.

So, if you compare this expression with that we know that now C n is equal to C n prime, so, essentially the coefficient of s in the numerator of in our quotient gives the capacitance and will have to look at what is how k n can be related to a r resistance. So, if you then again compare this particular form with the Cauer recursive unit which is essentially if you look at this particular term over here, when you are looking at 1 by Z t h you would have S C n plus one by this particular term in the denominator. So, we have or R n plus Z t h of n minus 1 is 1 by k n plus reminder of s divided by P n of s.

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So, you could then rewrite this particular expression in the form this also would be equal to 1 by k n minus reminder of s remainder at stage n. So, essentially if you simplify this particular expression you will get it to be the same as this expression ((Refer Time: 13:53)). So, again if you now compare this with our the expression of impedance of our Cauer recursive unit, you can see that the 1 by k term now would correspond to R n in this particular ((Refer Time: 14:17)).

If you look at compare these two expressions you will see that 1 by K n corresponds to R n and your Z c t h of n minus one is this second term over here which is minus remainder n of S by K n divided by K n P n of s plus remainder n of S, so this is essentially your p n minus 1 of S by Q n minus 1 of s. So, you apply the same procedure at the next level see you will get the terms for C n minus 1 and R n minus one till you reach the first C 1 and R 1. So, you would essentially be able to get the R n c parameters of your Cauer network. So, the other question is how to if you are given a network, which is in the Cauer form, how to transform it to the Foster form.

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So, you are given say Z c t h of n is e n of s by Q n of s. So, to actually do such a transformation what you would do is first determine roots of Q n of s. So, this would be your time constants 1 by R i C i and then you do a partial fraction expansion of P n of s by Q n of s. So, you find the residues of the partial fraction expansion P n of s by Q n of s. So, to avoid is, so your 1 by C i would correspond to your, so this 1 by R C is your omega i.

So, you from your roots of your expression you can find what your R C terms are and from your k i terms which are the residues of your partial fraction expansion you know what your C i's are, which are essentially 1 by K i. So, once you have the ability to go from one form the Foster form to the Cauer form and back you can actually build the overall thermal impedance network of your power module, your interface layer and the heat sink.

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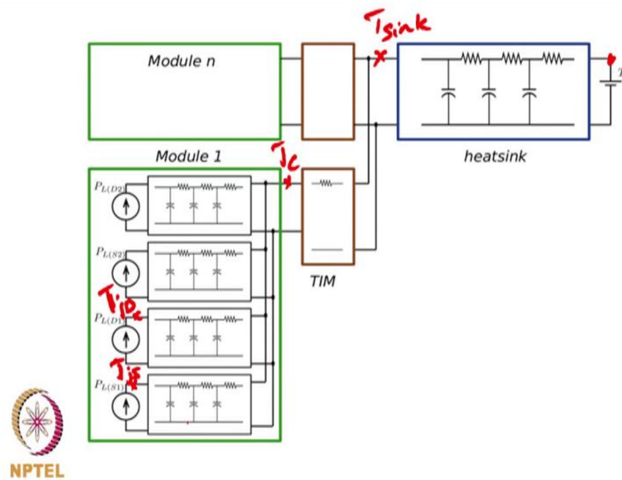

And get the overall thermal equivalent model for a, which can be used for dynamic thermal evaluation. So, essentially what you would have is dynamic thermal model for your junction temperature to your sink. So, this would be your T j of your semiconductor switch this would be T of your case and this point would be T of your sink and this point is the ambient temperature. Similarly you could determine the T j of your diode and similarly for the remaining switches that are located within your power module, if you have multiple power modules.

Now, located on the same heat sink, you could add more modules to the same heat sink, your thermal interface material is essentially a very thin layer of the order of tens of micron. So, a it has considerable thermal resistance, but not much thermal capacitance, so you might be able to make use of a simplified model, for that your models for your the power module would have some thermal heat capacity and some dynamics associated with it.

And you typical power modules can have thermal time constants which can be of the range of even up to 100’s of milliseconds you look at the thermal dynamics of larger heat sinks it can be of the order of seconds to minutes or very large heat sinks can even take hours to reach thermal equilibrium, depending on the form the cooling that is being used. So, you one would be able to form the overall thermal model of your overall network, one thing to look at to understand in such a model is that, if you are looking at the power

loss variation over a fundamental cycle. So, you are talking about fifty milliseconds would be a quite small n typical application. So, your T j variation during 50 Hertz variation might be of the order of a few degree centigrade.

Whereas, the time constants involved in the overall response might have considerable effect to in your considering transients that are of the order of 100's of milliseconds to seconds. So, in applications where say your starting a induction machine, your motor might take milliseconds, 10 seconds to start up then your you might have a over current or higher current levels during such duration. You might have say wind turbines, where you might have a wind guest which can provide more power.

So, you might have transient durations, where you are having higher powerful to your system, you might have say solar applications, where you might have periods of shadows clouds going across shadows moving across the system, you can also have faults in your grid and we saw that for many faults your circuit breakers might take 100's of milliseconds to operate. So, if you want your power converter to ride through a fault you might end up having higher current levels for a duration, which might be the order of 100's of milliseconds also in standalone applications your loads might start up and your in rush currents of your loads might have a higher power level.

So, evaluating the dynamic thermal characteristics of the your semiconductors becomes a important issue, we also will see that the evaluating the dynamic thermal characteristics has implications on the reliability of the semiconductors. So, for that will have to take a closer look at the structure of a power semiconductor module.

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Failure Measures for Semiconductors

- Mean time between failure (~~MBTF~~ MTBF)
- Mean time to failure (MTTF)
- Failure in time (FIT)

Random failures rates corresponding to flat region of the bathtub curve will not provide estimate of service life due to ageing and end of life effects.

But, before we do that will look at some of the issues of a reliability and failure in a power semiconductors. So, if you have a power semiconductor and you ensure that a under all conditions you are operating the device at a voltage less than it is rated voltage even ensuring that this spikes are below your rated voltage you are ensuring that you are operating always at a current level less than the rated current.

And you are also ensuring that on a steady state and also on a dynamic bases your junction temperature is held below the maximum junction temperature, then one could possibly operate the semiconductor for a very long duration without causing damage. But, practically people have seen that electronic equipment in the field fail and people have a ascribe random failure characteristics to it and run statistical analysis to look at a attributes, such as what is the mean time between failure. So, for a repairable system mean time between failure, so the M T B F is the time duration when you send out a component get it once you get a component back from repair and the next point when you are actually sending it out for a repair.

So, the duration between ah between is the MTBF. So, these are typically for repairable components for many components you might once it fail it may not be a repairable. So, you might have to throw it out or the duration under, which it is repair would be of no use, so people also talk about mean time to failure in a D G application when your power converter is down the overall D G system is not generating energy. So, MTDF might

actually be a better attribute to look at what is the failure characteristics of a power converter another way of looking at a failure is failure in time and failure in time is actually a quantity, which a is one failure.

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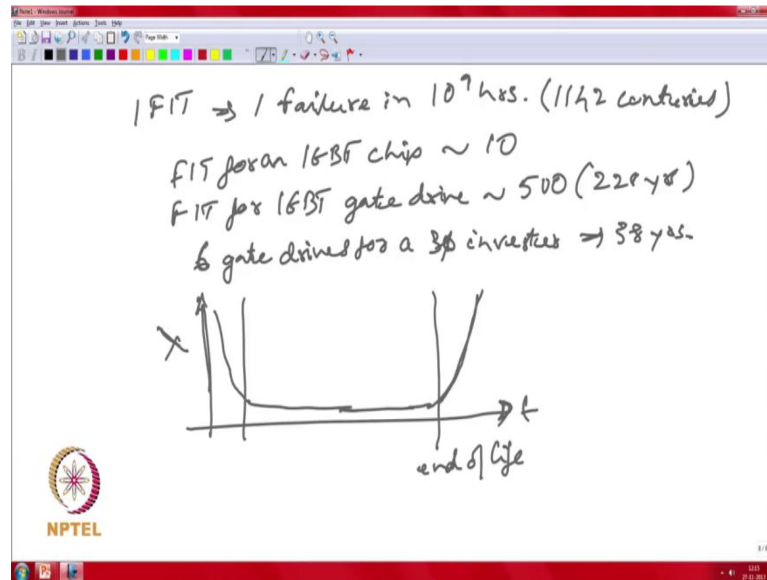

So, having a 1 FIT implies that you have 1 failure in 10 to the power of 9 hours, 10 to the power of 9 hours is actually a very, very long time if you convert it to centuries this corresponds to about 1142 centuries, so it is a really long time. If you look at the random failure rate associated with a IGBT chip. So, is of the order of 10 your the fit rate for the IGBT gate drive is of the order of 500, so if you now calculate that into years this corresponds to about 228 years. If you look at the fit rate then for a the gate drives of a three phase power converter system. So, you would have 6 gate drives.

So, you are talking about a now 38 years would be the expected say random failure rate, but many times the random failure does not give a true picture of when the device might actually fail, because if you look at the random failures they correspond to the point where your device operates under conditions of low failure rates. So, we know that a typical devices have this bath tub curve, so you are looking at your failure rate initially you are failure rate might be high because of in fin mortality, but once the component enters into service you will have a low failure rate.

And if you are using this particular component to determine your random failure rates, but you know that you might be under estimating the time because it is some point of

time your failure rates would start going up again, because of end of life issues. So, it is quite important to actually look at what is the end of life, what is the service life of the equipment, due to the end of life fixed to get a better picture, for how long we could expect a component to actually last. So, if you look at a typical power semiconductor module you would have ageing effects, because of a variety of reasons.

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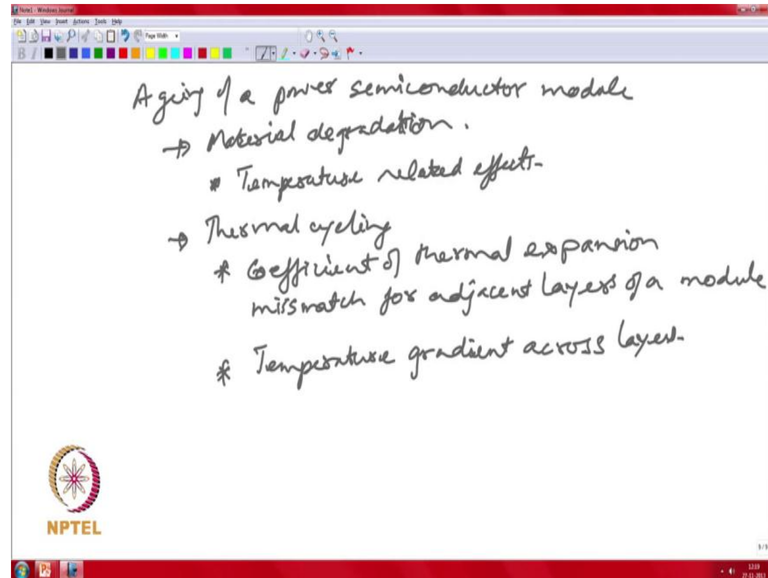

You might have just the regular material degradation, because of the temperature effects. So, so one can one knows that higher temperature can actually degrade material at a faster rate. So, there might be material degradation a important component of a ageing is actually thermal cycling and essentially thermal cycling is because you have a structure of the power module with a different materials and you have coefficients of thermal expansion for the different materials that consist that go into the power module.

And if your device heats up to some T j max the maximum junction temperature, the expansion of the different materials would be different, which means that ah you might end up with a structures that one to buckle or change it is shape. So, one is because of the coefficient of thermal expansion mismatch also another factor to keep in mind is that even if you have closely related thermal coefficient of expansions your temperature is not uniform adjacent layers might be sitting at different temperatures. So, your junction temperature might be 125 your case temperature might be 70 degrees, so the actual

temperature is different across the different layers. So, for example, you might have silicon which a might be sitting on top of a ceramic layer.

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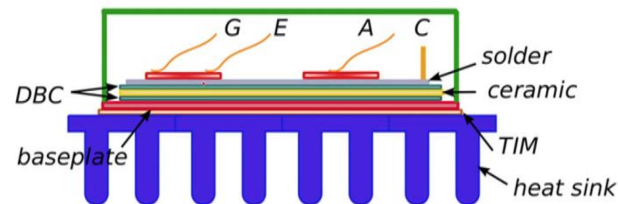
IGBT Module layers



And the ceramic layer say you might have your chip sitting on top of a ceramic layer and at 25 degree centigrade room temperature you might have the silicon chip dimension to be may be 1 centimeter and that might match your ceramic layer. But, at 125 degree centigrade your silicon might expand from say 10 mm to 11 mm, but your ceramic might expand from 10 mm to 12 mm, which means that essentially the two structures are now having a mismatch and it is trying to buckle over or develop cracks at the corners.

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Package Failure Mechanisms [2]

Fatigue failure due to temperature cycling.

- Dielectric cracks
- Wirebond lift or broken
- Solder fatigue
- Delaminated or lifted die

[2] Failure Mechanisms and Models for Semiconductor Devices, JEP122E, JEDEC standards and publications.

So, you could have a variety of a different concerns when you are operating a such a power module, you would have a stress build up across layers, because of your thermal characteristics and you might have cracks in your dielectric. So, your a different points of the dielectric might expand at different rates and from cracks, wire bonds are used to attach the chip to your external terminals that is how typically a silver or aluminum might have a different expansion coefficient; it might actually break or it might lift off you have solder joints within in the module.

So, those points would develop fatigue your chip itself might get delaminated from your bottom your insulation itself might get delaminated from your base plate and you might end up with a lifted dies etcetera. So, after these problems like wire bond lift off, delaminated corners of the chips you end up with a non-uniform current density within your chip, which can actually cause even further heating, which can actually further accelerate the temperature related degradation within the power module.

If you look at the overall structure of the power module, you have essentially the heat sink at the bottom, typically commonly use material for the heat sink might be aluminum you might also cause copper if you are looking at higher heat storage capacity. You have your thermal interface material or essentially the thermal Greece between your base plate and the heat sink, which is a thin layer you have a base plate. And the base plate is essentially the bottom of your module which you tighten with screws to your heat sink

commonly use material for the base plate is either copper or people also look at aluminum silicon carbide, which has the better match or with the thermal expansion quotient of silicon above the base plate is actually the ceramic layer.

So, the ceramic layer to the base plate is has a direct copper bonding which is essentially a way of bonding a ceramic to a copper structure and on the upper side of the ceramic is also direct bond at copper, which is used to ensure that you get can do a solder joint within between your silicon chip to your upper side of your ceramic.

So, you have then on top of the DBC layer direct ah bonded copper, you have a solder layer which is used to connect the chips to your bottom of the module. So, essentially if you look at the chip, if it is a IGBT chip the bottom would correspond to the collector if it is a most fed typically, you are looking at the drain at the bottom, if you looking at a diode is essentially the cathode at the bottom of essentially the module and at the top. So, after that you have the silicon of the chip on top of that you might have oxides gate oxides you might have aluminum metallization for a contact to external terminals you would have wire bonds that are then used to connect to external terminals you might have passivation layers.

You would have potting material and then on top would be the casing typically a plastic casing to ensure that already structures are held within the power module. So, you can see that it is a sandwich arrangement often you try to select materials for ceramic your base plate. For example, the ceramic might be aluminum oxide, aluminum nitride, aluminum nitride has a better match of thermal expansion coefficient with your silicon, so it would be able to stand more thermal cycling.

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Coffin-Manson Model

Fatigue failure due to temperature cycling.

$$N_f = A_o \left(\frac{1}{\Delta\varepsilon_p}\right)^{B1}$$

where, N_f = number of cycles to failure, A_o = material dependent constant, $\Delta\varepsilon_p$ = plastic strain range, $B1$ = empirical constant.

$$\Delta\varepsilon_p \propto (\Delta T - \Delta T_o)^{B2}$$

$$N_f = A_o (\Delta T)^{-q}$$

where, ΔT_o = Temperature variation in elastic region, q = Coffin-Manson exponent.

So, to look at the failure when you have a such cycling n structure one model that is commonly used when you are looking at a fatigue failure in a mechanical structure is the Coffin Manson model which relates the number of cycle to failure to the strain that happens within the structure. So, essentially the original model was proposed for ductile materials and later on it was seen that you could actually fit the model for British structures like silicon chips or ceramic layers etcetera.

Essentially you have a exponential relationship between the number of cycles to failure to the strain that is applied within the object under test and A naught and B 1 are essentially coefficients associated with this model. So, the again what we are looking at is a situation where you looking at a strain a being the result of a stress being applied on the material. And in this particular case the stress that is being applied is the your temperature of your particular junction and because your temperature has increased to some particular point.

Your different layers now apply different levels of force at the interface layers and deform the structure. So, typically when you apply a stress on a object, you would initially have something called the elastic range, where you take the stress away and it comes back to the normal point. But, beyond a beyond the a yield point you would essentially have plastic strain range where you apply a stress and then you take away the stress you may not actually return back to the original point.

So, what is looked at for the cycles to failure is the range for plastics strain, a also we know that the this particular strain range is proportional to the temperature difference of the cycles through which you heat up and cool down the temperature the temperature of the junction. You might have some temperature range corresponding to the elastic stress and then the balance would correspond to the temperature range, where you might actually have plastic deformations.

So, overall if you look at it the delta T naught which might correspond to the temperature variation the elastic range might be quite small compared to the overall temperature variation. So, you could simplify it to be of the form that the number of cycles to failure depends on your variation of your junction temperatures to some exponent A naught and Q are essentially constants.

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IGBT Module Thermal Cycling Tests

Test performed on IGBT modules for traction applications[3]:

$$N_f = A_o \, (\Delta T_j)^{-q} \, exp \left(\frac{Q}{RT_m} \right)$$

where, N_f = number of cycles to failure,
ΔT_m = Mean temperature during the cycle (K),
$\Delta T_j = T_{max} - T_{min}$ during the temperature cycle,
q = Coffin-Manson exponent,
Q = Activation energy constant,
R = gas constant,
A_o = experimental constant for the module.

[3] Held, M., et.al., "Fast Power Cycling Test for IGBT Modules in Traction Application", in Conf. Proc. Power Electronics and Drive Systems, 1997.

So, some of this effects of temperature cycling people started investigating the mid 90's and some of the early test were conducted on traction module, in traction applications. So, if you have a train or a tram or a electrical vehicle you have a situation where when you accelerate at start you are applying a lot of current through your motors, so you have a higher power loss. So, once you reach steady speed your power a level comes down and then when you decelerate you might be regenerating.

So, again the power level can go up and then when you are at stop your power level is a closed to zero. So, traction applications and transportation applications see a lot of

thermal cycling. So, only there are initial concerns when IGBT inverters we are failing in the field a quite rapidly, when initially applied in traction systems and some of the initial studies indicated that the number of cycles to failure can be related to the junction temperature and also the mean temperature through some activation energy type of expressions.

And one could then make use of expressions such as this to evaluate how many thermal cycles can given module be used before it actually starts failing. More recent work related to thermal cycle failures in IGBT modules have also indicated that there can be dependency on the durations of during which of power loading is being done. The amplitude of the current that is being passed through the connections into the chip, your voltage rating of your semiconductor. We saw that the drift region of the semiconductor depends on the on the voltage ratings. So, a thicker chip can have a different thermal cycle compared to a thinner chip.

You would also have dependency on the diameter of the wire bond, so a thicker wire bond might experience a different failure rate compared to a thinner wire bond. So, without, we will continue will look at this expression for the cycles to failure and look at an example to look at how we could use this in a design.

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Example: IGBT Module Thermal Cycling Design

A load turns ON and OFF once and hour. Thermal steady state is assumed to be reached quickly. $T_{ambient} = 55^oC$. What would be the lifetime of the equipment is the $T_{j(max)}$ is designed to be 125^oC, 120^oC, or 110^oC when the device is ON.

The parameters for the thermal cycling model are: $q = 5$, $Q = 7.8 \times 10^4 J$, $R = 8.314 J/mol/K$, $A_o = 640$.

$T_{j(min)}$ (^oC)	$T_{j(max)}$ (^oC)	ΔT_j (^oC)	T_{jm} (^oK)	N_f (cycles)	Life (years)
55	125	70	363.15	6.32×10^4	7.2
55	120	65	360.65	1.1×10^5	12.5
55	110	55	355.65	3.64×10^5	41.5

Where you are looking at what should be the maximum junction temperature that one could consider when your looking at a design application. So, in this example we are

looking at a load, which turns on and off once in hour, 24 hours in a day around the year and we are assuming that the thermal steady state is reached quickly. So, when it is off it quickly reaches the ambient temperature of 55 degree centigrade and the question is when the load turns on what should be the system design should be choose at T j max of 125 degree centigrade or 120 or 110.

So, as you ensure that your life of this particular equipment meets your target. So, the parameters for this thermal cycling model used are the exponent being equal to 5 q the activation energy related term is 7.8 into 10 to the power of 4 joules, R is the gas constant and a naught is a 640. So, if you have a your T j min which is essentially your ambient temperature, when it is off and T j max to be 125 you delta T j would then be 70 degrees.

And your mean temperature is essentially 125 plus 55 by 2 in Kelvin this is three sixty three degree centigrade and you can plug this to the expression over here to evaluate the cycles to failure. And you can get an expression for then the life of the equipment because we know there is one cycle in hour. So, you take this divided by the number of hours number of days a year and you get 7.2 years. So, you can expect life of the order of seven point two use if you are designing with a junction temperature of 125.

If you reduce your junction temperature, maximum junction temperature to 120, then your delta T reduces your T j mean reduces by some extent your number of cycles to failure now increases and you get a about 12.5 years. If you reduce further reduce your T j max you can end up now with a life time of the order of 41 years. Again these are design numbers does not mean that your actual inverter might last for 41 years you might have other factors which can cause different types of failure.

But, these are indicative numbers to see whether this particular issue might be a concern in your particular application. So, one way of addressing say you have an equipment which is intended to last for 10 years then definitely this may not be a good way to actually do the design you might have to select a different temperature. And one way of ensuring that you can actually do that is by going for a higher rated, current rating of the device which would have typically a lower on state resistance with lower power dissipation.

Also your higher current rated device would have lower thermal impedance resulting in a lower T j max you can get a improvement in your cycle life time. One thing to keep in mind is a typical data sheets do not provide this level of detail of IGBT data. So, to get detailed data from on the modules to do evaluate cycle life etcetera, one might actually have to contact a design engineers or application engineers from the company to actually get the detailed information.

Another thing to keep in mind is that in typical applications it may not be just two temperatures that one is operating it you are may not be just operating between say 55 degree centigrade and 120 degree centigrade. You might have number of temperatures over which the equipment would operate.

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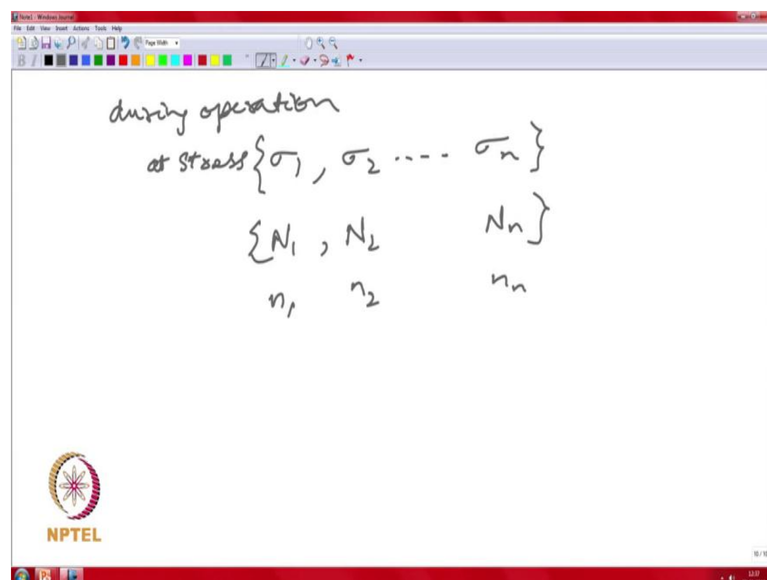

So, you might operate at stress sigma 1 for some duration followed by sigma 2 up to say sigma n and you might have different cycles to failure rate for the different temperature stretches stress that are being applied on the component. So, corresponding to a sigma 1 you might have n 1 cycles to failure and corresponding to sigma 2 you might have n 2 cycles to failure and N N cycles to failure. So, using the expression we could actually calculate the cycles to failure for the actual for under these varying conditions of stress, but your actual applications may not just operate at N 1 or N 2 cycles.

You might out actually operate for some small n, n i small n 1 cycles under stress condition sigma 1, small n 2 under sigma 2 and small n n for sigma n. So, the question is

how to actually consider conditions, when you are operating under conditions of varying stress rather than just switching back in forth between a minimum and maximum.

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Palmgren-Miner Rule for Damage Accumulation

Let N_i be the expected cycles to failure due to operation under stress σ_i.
Let n_i be the actual number of cycles operated under this stress level.

Let D_f be the total damage that an object can tolerate before becoming non-functional and D_i is the damage caused during operation i. Then $\sum_{i=1}^{n} D_i = D_f$ or $\sum_{i=1}^{n} D_i/D_f = 1$.

For fatigue failure under conditions of varying stress,

$$\sum_{i=1}^{n} n_i/N_i = 1$$

So, this can be done by one way to look at this is what is called the Palmgren Miner rule for damage accumulation. So, let N i be the expected cycles to failure under stress condition sigma i and small n i be the actual number of cycles operated under this a particular stress level sigma i. So, essentially for a given component let D f be the total damage that you can actually subject the object before it becomes non-functional. And let D i be the number of the damage caused by operation under condition i.

So, if you are operating under stress condition i and d i is the damage that is cause under stress condition I, then essentially what you are doing is operating under varying stress conditions you are saying that you could some over all the stress conditions. And once you reach d f then the component is considered failed or another way to look at it you can look at the damaged on a normalized bases. So, you take the damage under your i'th condition divided by your damage to failure and once that sums up to 1.

Essentially here what you have done is still we have divided both sides were D f, essentially when you are normalized damage reaches 1, then essentially you have reached your end of life point. So, for the cycles to failure condition you can then express this as the summation over the number of actually cycle of operations divided by

the cycles to failure numbers when that accumulates to 1, then essentially you would end up having thermal cycling failure of this particular component.

One thing to consider when your applying such a concept is that a essentially what you are doing is you are assuming that the damage accumulates and essentially your assuming that there is linearity in the way the damage accumulates. For example, you might have a situation where you apply stress 1, which is larger and stress 2 which is smaller and you might your total damage at the end point of after application of stress two might be something.

And you could reverse the sequence you could apply stress 2 first and then stress 1. So, the accumulation of damage assumes that you get the same level of stress irrespective of whether you apply the larger stress first or the larger stress second. So, you are neglecting sequence effect, because if you have already damage applying the same effect might cause further damage you are neglecting sequence effects, when you are actually applying this particular rule. So, this is an approximation, but it gives you a way of looking at how to accumulate damage when your operating under conditions of varying stress. So, will look at an example now of a situation, where you are operating under conditions of varying stress.

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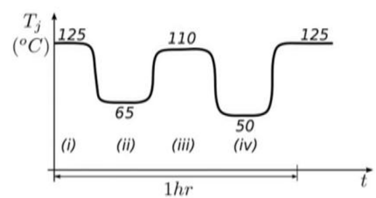
Periodic Loading of the Power Converter



	ΔT (°C)	T_m (°K)	N_{fi} (cycles)	D_i/D_f
(i)	60	368	9.61×10^4	5.2×10^{-6}
(ii)	45	361	6.88×10^5	7.27×10^{-7}
(iii)	60	353	2.84×10^5	1.76×10^{-6}
(iv)	75	361	5.35×10^4	9.35×10^{-6}
Total normalized damage per hour				1.7×10^{-5}

We before that a example will look at what could be the procedure that we could use to actually sum up the stress when you are operating under such varying stress conditions.

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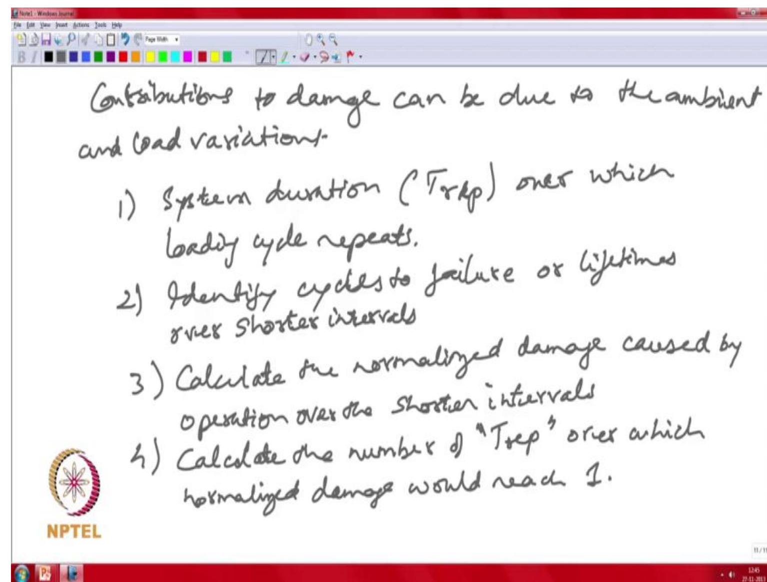

So, whether contributions to stress can be not just the loading can be just the ambient itself varying over time and many power applications you would also have some reputation rate of loading or ambient situations. For example, in a factory you might have the production duration might repeat on a daily bases.

So, the equipment in the factory might get loaded under some set of conditions on a daily bases or in a transportation application you might have a typical drive cycle, which is repeated on a daily bases. There might be some variations on weekends, but you might have some then weekly patterns for a D G applications for example, in a wind turbine you might have a patterns of winds, which might see random. But, over longer durations your loading levels might have statistical distributions from which might lead to similar level of loading repeating over multiple months.

So, depending on your application you can have repetition durations of loading over which you are looking at how the temperature junction temperature is varying over time. So, the first thing to consider is your T rep, so the second step is to identify cycles to failure or lifetimes over shorter intervals and then you calculate what is the normalized damage and then you calculate.

So, you calculate the number of repetition periods over which the normalized damage would reach one would give you a indication of what your expected cycle life service life of your equipment is for an actually operating condition. So, will look at an example for

doing this particular exercise in the next class, but we can see that evaluating the junction temperature, the temperatures of various components are actually a very critical part of the power electronic design.

Thank you.