Design of Power Electronic Converters
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Lecture 38
Power Loss - I

Welcome to the course on Design of Power Electronic Converters. Today we will begin with the module of Thermal Design. To understand thermal design first, we have to know the different power losses that take place in power electronic converters.

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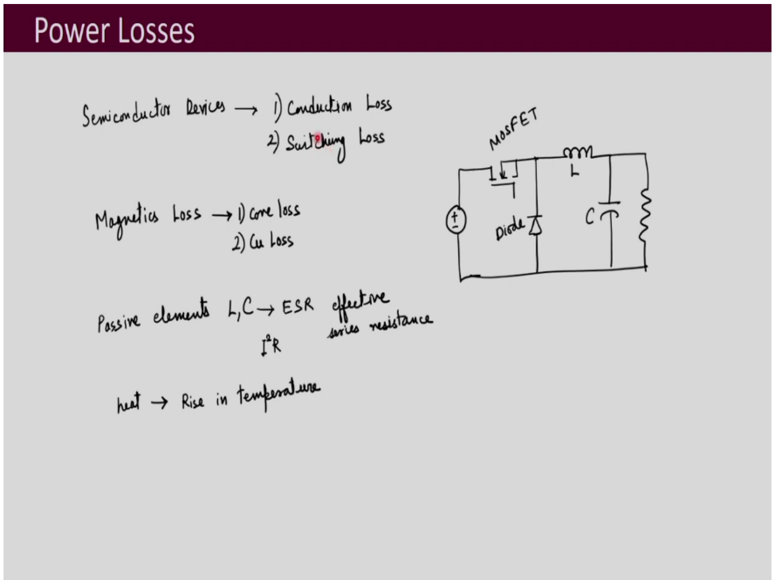

Power Losses

Semiconductor Devices → 1) Conduction Loss
2) Switching Loss

Magnetics Loss → 1) core loss
2) Cu Loss

Passive elements L, C → ESR effective series resistance
I^2R

heat → Rise in temperature

The main power loss that take place in power electronic converters is because of semiconductor devices. And you might be already familiar there are two types of it, one is your conduction loss and second is your switching loss. Now, let us recall the buck converter circuit. So, in buck converter you had a switch. So, here the semiconductor device losses will be taking place in this MOSFET and also in the diode.

But apart from this what we see is that that the converter also have got this L which is magnetics. So, that will also have its own loss, so magnetic losses. So, they also contribute to the total loss and there are two types of it one is your core loss and the second is your copper loss. Now, both of these core loss and copper loss we will be discussing when we discuss magnetic design. Then we what we see is that there is C as well, capacitance.

So, we have for whatever these passive elements that we have got these will have their own series resistance which is called as the ESR effective series resistance and they will have their own I square R losses. So, what we can say is that different passive elements in any power electronic converter take your L, C and whatever others may be there, their ESR which is your effective series resistance, these also contribute to the total loss in the form of I square R losses.

Apart from this, these converters are realized by designing PCBs printed circuit boards and those PCB traces will also have their own ESRs and that will also lead to I square R losses. Apart from there they may be drivers and different ICs may be there in any converter and several sensing circuits may be there which might be having their own passive elements. So, all of them will have some loss, which will be mostly in the form of I square R losses.

So, different elements in your converter miscellaneous elements in your converter, they also contribute to the total loss taking place in any converter. Now, all these loss, these power loss that finally occur in the form of heat, the heat of the device and that leads to rise in temperature. Because of which, what happens is that if we exceed the temperature, which is the maximum limit that is specified in the datasheet of different devices, then that may damage the device.

So, we always have to ensure that we do cooling and we do cooling in such a way that the maximum temperatures of different devices are not exceeded. Now, when we discussed your semiconductor devices at that time, I had shown you that most of the data sheets they give the junction temperature. So, the maximum junction temperature that the device can withstand, the power semiconductor device can withstand.

So, then that is something should not be exceeded and for that cooling has to be done, the devices have to be cooled. Now, all these other different kinds of losses that we are seeing magnetics loss and passive loss, this we will not be discussing here, we will be mainly discussing the loss that takes place in your semiconductor devices your conduction losses, switching loss and how can we cool the semiconductor device that is what we are going to discuss.

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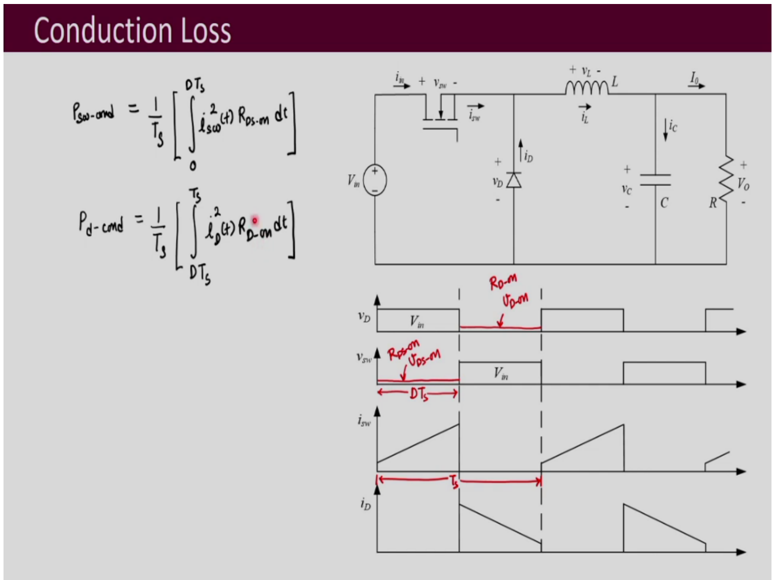

Conduction Loss

$$P_{sw\text{-}cond} = \frac{1}{T_s}\left[\int_0^{DT_s} i_{sw}^2(t)\, R_{DS\text{-}on}\, dt\right]$$

$$P_{d\text{-}cond} = \frac{1}{T_s}\left[\int_{DT_s}^{T_s} i_D^2(t)\, R_{D\text{-}on}\, dt\right]$$

So, this is your familiar buck converter circuit. So, let us see the conduction loss first. Now, these are the waveforms that we have discussed before in the very first module and there we had seen that that this diode, this is the voltage waveform that appears across the diode. So, when the switch is on that means, for your this time period DTS the switch is on and at that time for an ideal device the voltage across the device will be zero and at that time the diode blocks.

And so, then Vin is the voltage that is going to appear across the diode and when this switch turns off at that time this diode conducts. Now, ideally there will not be any voltage across the diode when it is conducting but in reality there will be. And let us say there is some this small voltage drop which is your vd-on we can see that and we can also associated with on state resistance and we can call it as let us say Rd-on.

Similarly for the switches, for the MOSFET as well there will be little on state voltage drop we can call it as vds-on. And there is on state resistance also of MOSFET this we had discussed before it is called it is Rds-on as the on state resistance. Now, this is the switch current and then when the switch does not conduct it is 0. Now, in reality there will be some small leakage current it is usually so small that we can ignore it for loss calculation purpose.

And this is the diode current where when the diode is not conducting, it is 0 and when the diode conducts this is the current that flows through the diode. Now, we can write the expressions for the conduction loss. So, this is your total time period Ts and corresponding to that the switching frequencies fs. So, we can write the conduction loss that takes place when the switch is on that will be

$$P_{sw-cond} = \frac{1}{T_S}\left[\int_{0}^{DT_S} i_{sw}^{2}(t)R_{DS-on}\, dt\right]$$

So, what we observe from this expression is that this conduction loss takes place that means when the device is conducting that is what is your conduction loss and the main thing which is responsible for the conduction loss is a small voltage drop that appears across the device while it is conducting. So, those two multiply then we will have some loss because of it.

And we can write either it as the multiplication of the constant voltage drop and current or we can also write it warm up I square R losses. So, that is what if we integrate this current, so square of it multiplied by Rds-on in the interval 0 to DTs and divided by 1 by Ts. So, that is the conduction loss that will be taking place for one switching time period.

Now, similarly, we can write for the diode also. So, the diode conduction loss will be Pd-cond

$$P_{d-cond} = \frac{1}{T_S}\left[\int_{DT_S}^{T_S} i_{D}^{2}(t)R_{D-on}\, dt\right]$$

Now, here, we have to multiply it with the diode on state resistance and not the MOSFET on state resistance.

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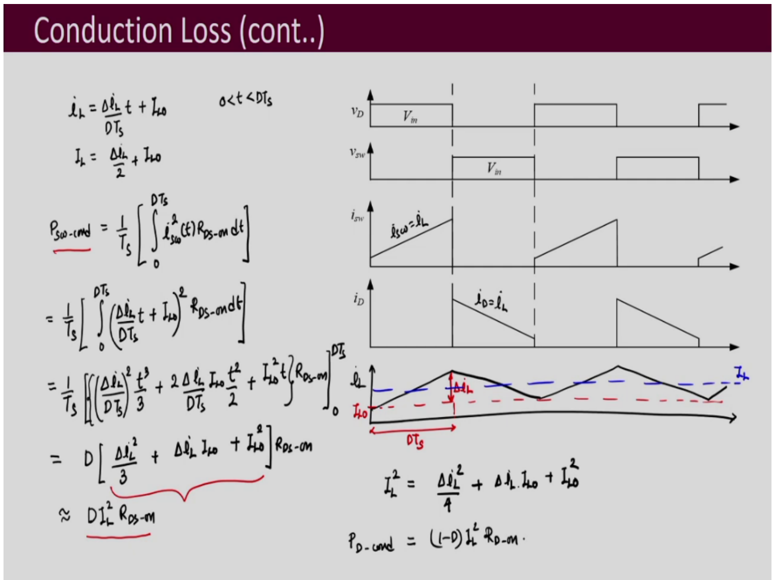

Conduction Loss (cont..)

$$i_L = \frac{\Delta i_L}{DT_s} t + I_{L0} \qquad 0<t<DT_s$$

$$I_L = \frac{\Delta i_L}{2} + I_{L0}$$

$$P_{sw\text{-}cnd} = \frac{1}{T_s}\left[\int_0^{DT_s} i_{sw}^2(t) R_{DS\text{-}on}\, dt\right]$$

$$= \frac{1}{T_s}\left[\int_0^{DT_s} \left(\frac{\Delta i_L}{DT_s} t + I_{L0}\right)^2 R_{DS\text{-}on}\, dt\right]$$

$$= \frac{1}{T_s}\left[\left\{\left(\frac{\Delta i_L}{DT_s}\right)^2 \frac{t^3}{3} + 2\frac{\Delta i_L}{DT_s} I_{L0} \frac{t^2}{2} + I_{L0}^2 t\right\} R_{DS\text{-}on}\right]_0^{DT_s}$$

$$= D\underbrace{\left[\frac{\Delta i_L^2}{3} + \Delta i_L I_{L0} + I_{L0}^2\right]}R_{DS\text{-}on}$$

$$\approx D I_L^2 R_{DS\text{-}on}$$

$$I_L^2 = \frac{\Delta i_L^2}{4} + \Delta i_L . I_{L0} + I_{L0}^2$$

$$P_{D\text{-}cond} = (1-D) I_L^2 R_{D\text{-}on}.$$

The further if we want to simplify those expressions that we just wrote for conduction losses of the MOSFET and the diode, we have to recall that the switch current and the diode current actually is formed from the inductor current. So, this waveform, this we had discussed before. Your inductor current waveform shape you might remember. So, this is the shape of the inductor current. And this is equal to i sw equal to i L when it is conducting and i D equal to i L when they will just conducting.

So, then we can use the inductor expression. So, we can write this inductor expression i L as

$$i_L = \frac{\Delta i_L}{DT_s} t + I_{L0}$$

$$0 < t < DT_S$$

Now, what is this IL0? So, this one is your IL0 and then whatever is this change in current the ripple that is delta i L. And of course, we know that this is the time period DTs. Now, this holds true for the interval DTs, from 0 to DTs. And this average i L we can write it as

$$I_L = \frac{\Delta i_L}{2} + I_{L0}$$

What is capital IL? This also you might recall, this is the average i L that we can write here. Now, further if we derive this the same conduction loss of the switch and try to solve it,

$$P_{sw-cond} = \frac{1}{T_S}\left[\int_0^{DT_S} i_{sw}^2(t)R_{DS-on}\, dt\right]$$

So, if we substitute for i sw, so this will become,

$$P_{sw-cond} = \frac{1}{T_S}\left[\int_0^{DT_S} \left(\frac{\Delta i_L}{DT_S}t + I_{L0}\right)^2 R_{DS-on}\, dt\right]$$

further we can solve it. So, what you will be getting is,

$$P_{sw-cond} = \frac{1}{T_S}\left[\left\{\left(\frac{\Delta i_L}{DT_S}\right)^2 \frac{t^3}{3} + 2\frac{\Delta i_L}{DT_S}I_{L0}\frac{t^2}{2} + I_{L0}^2\right\}R_{DS-on}\right]_0^{DT_S}$$

so this is what you will be obtaining. And now further if you solve it what you will be obtaining it as

$$P_{sw-cond} = D\left[\frac{\Delta i_L^2}{3} + \Delta i_L I_{L0} + I_{L0}^2\right]R_{DS-on}$$

Now, if we square this term, so that is your IL square that you can write it as

$$I_L^2 = \frac{\Delta i_L^2}{4} + \Delta i_L I_{L0} + I_{L0}^2$$

So, what we see here is that this $\left[\frac{\Delta i_L^2}{3} + \Delta i_L I_{L0} + I_{L0}^2\right]$ term is almost equal to i L square approximately equal because here this is by 3 i L square by 3 and this is i L square by 4. So, approximately we can equate it and so we can write this as

$$P_{sw-cond} \approx D\, I_L^2\, R_{DS-on}$$

So, from this what we see is that this Psw conduction loss, the switch conduction loss in a simple way we can write it as equal to the duty ratio multiplied by the average of the square of the inductor current and multiplied by the on state resistance of the MOSFET. Similarly, we can also write for the diode the conduction loss as PD-cond as

$$P_{D-cond} = (1 - D)I_L^2 R_{D-on}$$

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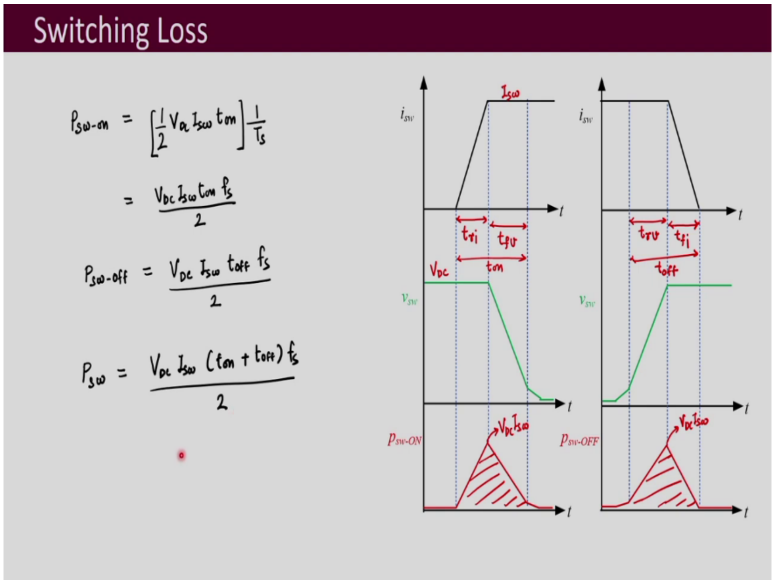

Switching Loss

$$P_{sw\text{-}on} = \left[\frac{1}{2} V_{dc} I_{sw} t_{on}\right] \frac{1}{T_s}$$

$$= \frac{V_{DC} I_{sw} t_{on} f_s}{2}$$

$$P_{sw\text{-}off} = \frac{V_{DC} I_{sw} t_{off} f_s}{2}$$

$$P_{sw} = \frac{V_{DC} I_{sw} (t_{on} + t_{off}) f_s}{2}$$

Now, let us look into the switching loss, switching loss obviously from the name, it takes things when the device is switching that is while it is turning on and while it is turning off. So, these waveforms we had seen before for any switching device, usually what we have seen mostly for transistors or even for diodes also what we saw is that during the turn on process, first the current increases and it increases to almost to the on state value.

At that time the switch voltage does not change and after that the switch voltage slowly this reduces and it becomes close to the on state voltage drop. And these two intervals are the main intervals in which the switching loss takes place. So, this interval is called as your tri the rise in current interval and this is the fall in voltage interval. So, tfv, we can write it as and the total of these the sum of these two is the on state interval.

So, this i sw the switch voltage it depends on what it is going to be during the off state, but for buck converter it will be equal to V in or if we have an H bridge converter it will be equal to Vdc. And here this will be equal to your the on state current and let us call that as equal to capital Isw. So, then if we want to know the loss, we have to multiply the current and the voltage. So, here we have multiplied the current and the voltage.

So, this is the instantaneous power curve for on state laws, so Psw-on. So, what we see is that that this is like a triangle. So, here this peak will be equal to Vdc multiplied by Isw. So, this is your Vdc into Isw. And the area under this triangle will be the loss that will be taking place, the energy loss. And if you take the average of it, then you get the turn on loss, the average turn on loss over one switching time period.

Similarly, for turn off, same thing, first the voltage builds up and we named this interval as trv and in the next interval when the voltage has built up close to the blocking voltage, then the current falls and we can call it as tfi and the sum of these two intervals is your mainly your the turn off interval.

Now, maybe getting confused with the device characteristics that we had studied when we discussed devices in great detail that there were some other intervals also that were present, but know that for switching loss estimation, we are simplifying it, we are only taking those intervals which contribute to majorly to the switching losses.

So, again, if we have to plot this instantaneous power at turn off, so this is also be again be like a triangle and here this peak will be equal to again same Vdc into Isw and this area under this triangle will be the energy loss that will be taking place during turn off. So, if we have to write the expressions for turn on, the on state switching loss rather the turn on switching loss Psw-on will be given as

$$P_{sw-on} = \left[\frac{1}{2} V_{DC} I_{sw} t_{on}\right] \frac{1}{t_s}$$

$$= \frac{V_{DC} I_{sw} t_{on} f_s}{2}$$

Similarly, for the turn off switching loss also, we can write it as

$$P_{sw-off} = \frac{V_{DC} I_{sw} t_{off} f_s}{2}$$

The total switching loss Psw for one switching time period will be given by

$$P_{sw} = \frac{V_{DC} I_{sw} (t_{on} + t_{off}) f_s}{2}$$

so this is what is the total switching loss that we obtain.

And this is a very simple expression which you can use it for a simple converter like a buck converter. So, where you have the bus voltage or the input voltage and then is your whatever is your Isw current that you are going to get you can also take the average current sometimes to simplify further and then you have the t on plus t off and the switching frequency divide by 2 that will give you the estimate of the switching losses.

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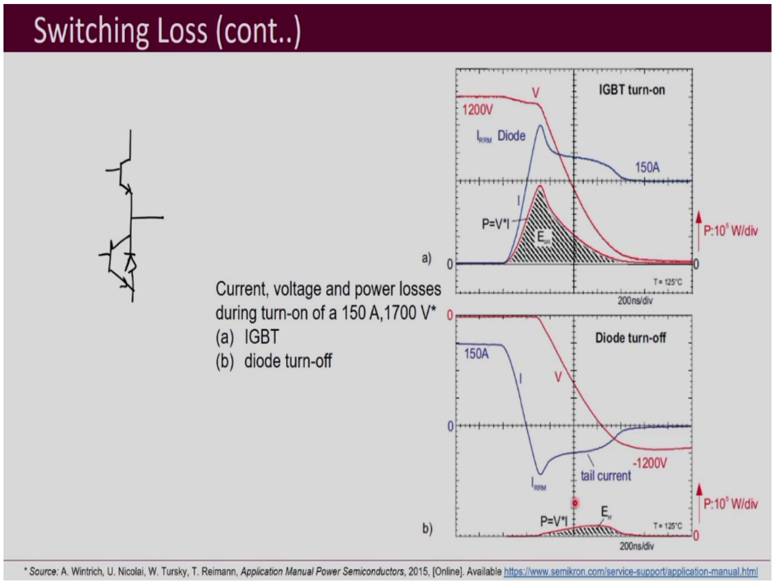

Switching Loss (cont..)

Current, voltage and power losses during turn-on of a 150 A,1700 V*
(a) IGBT
(b) diode turn-off

* *Source:* A. Wintrich, U. Nicolai, W. Tursky, T. Reimann, *Application Manual Power Semiconductors*, 2015, [Online]. Available https://www.semikron.com/service-support/application-manual.html

So, this graph I had shown you before also, this has been taken from the application manual from semikron where they are showing the turn on loss of an IGBT with a anti parallel diode in it. And for your H-bridge converter you may recall when one IGBT is turning on at that time and the diode is turning off. So, that is your this IGBT and here you have the diode. So, this diode turns off, this diode turns off when this IGBT is turning on. So, this diode turn off loss is shown here.

The diodes voltage is your building up and your current is becoming 0. Whereas, here the IGBT is turning on, so IGBTs current is building up and the voltage is reducing. So, this is the turn on loss and this is the turn off loss of the diode. So, what we see is that the diode loss is much smaller than the IGBT loss. So, that is why many times your when power loss calculations are done specially switching loss calculation then the diode switching losses are ignored.

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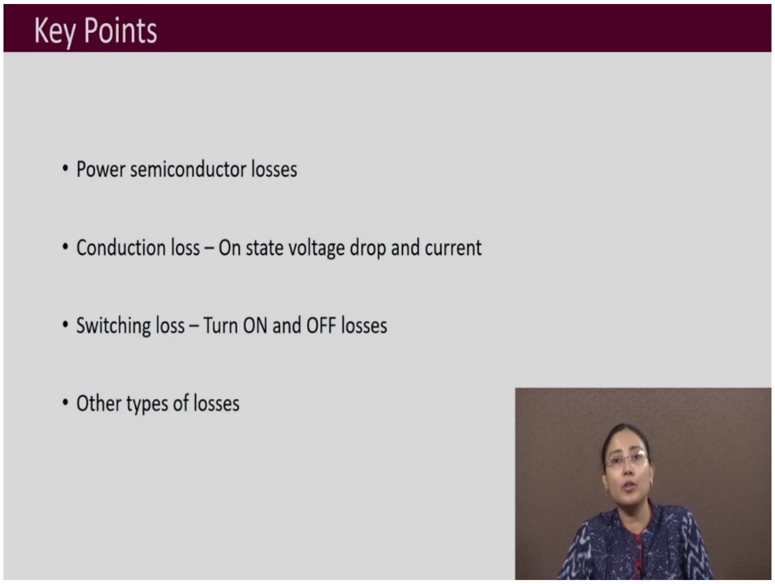

Key Points

- Power semiconductor losses
- Conduction loss – On state voltage drop and current
- Switching loss – Turn ON and OFF losses
- Other types of losses

So, the key points of this lecture are your main loss that take place in your power electronic converters are your power semiconductor device losses. Apart from that, there will be other losses because of the magnetics and several other passive elements and I square R loss is taking place in different elements of the converter.

And your power semiconductor device losses that is of two types one is your conduction loss and second is your switching loss. And conduction losses because of the on state voltage drop across the device and switching loss is because of the turn on and turn off when both the currents and voltages are high together for some amount of time. Thank you.