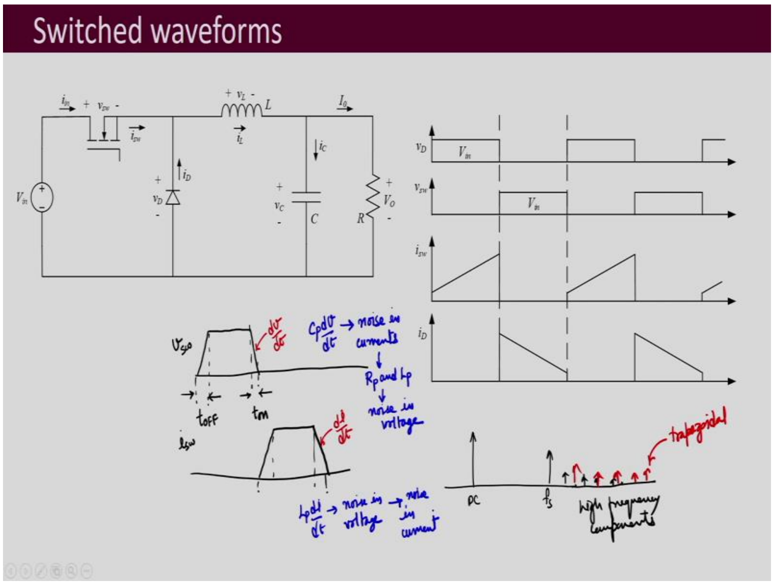
Design of Power Electronic Converters

Professor Doctor Shabari Nath
Department of Electronics and Electrical Engineering
Indian institute of Technology Guwahati

Lecture 56

EMI in Power Electronics

Welcome to the course on design of power electronic converters. We were discussing the module about introduction to electromagnetic interference. In today's lecture we will be looking into the sources of electromagnetic interference in power electronic converters. In the introductory lecture, I had told you that the main source of EMI in power electronics are the switched waveforms, the switch voltage and current waveforms.



So, you might be recalling this buck converter which we have been using again and again to explain the design concepts. So, here you see these voltage waveforms. This is the voltage waveform across this diode and then this is the switch voltage waveform across the switch and these are the current through the switch and the current through the diode. We observe that all of them are switched waveforms that means they change abruptly very quickly.

Now, these waveforms are drawn for ideal conditions, that means we did not assume any parasitics for the passive components and also for these power electronic devices we neglected all the non-idealities that these devices are having. These waveforms are drawn assuming that everything is ideal.

Even when we assume things to be ideal, then also if you do FFT analysis that means a fast fourier transform of these type of waveforms, then you will be seeing lot of harmonics at the high frequencies. So, if you were to draw the FFT, in this fundamental component the DC component is going to be present. As you go further, and if you keep on doing the FFT, apart from having the switching frequency component you will see lot of high frequency components that may be present.

Now, previously you might have studied how to do FFT of square wave or different types of wave form shapes and you know that in these fast fourier transforms they depend on the shape of the waveforms. So, here the nature of these waveforms are similar to square wave form.

Now, you also know that none of the devices are ideal. So, it will have a fixed turn on and turn off time or a specific turn on and turn off time. So, these voltages will be like this. That means they will be having a finite time to rise and to build these things. We have discussed in detail when we discussed the power semiconductor devices.

So, here you see that this is for the voltage building. That means, it is turning off and this is the turn on time. So, this is for the voltage and then similarly, when you see the current, the current also will take some finite time to rise and to fall. So, when you do the FFT of these, that will be slightly different for the case while you can trade that the nature of the waveform is trapezoidal.

So, from there what we see that that as turn on and turn off times changes and you may be having different spikes, all that will affect the frequency spectrum. The high frequency components may be present in that particular waveform. So, then that is going to affect the EMI performance or the electromagnetic interference problem will be affected by that.

So, it may increase or it may decrease depending on the nature of the waveform and it will be also dependent on the turn on and turn off times. Now, obviously, if turn on and turn off times are very fast or it takes very quickly, then this frequency spectrum will have higher content towards the range where conducted EMI and radiated EMI range is considered for EMI measurements.

So, we need to be careful while you are choosing the gate resistors designing the snubbers. So, turn on and turn off trajectories affect the EMI or you can say that these transitions in the devices are a source of EMI. The switched voltage waveforms are a source of EMI and they take to change the amount of time, which are sources of EMI.

Further you observe that this has got *dv/dt* and this has got *di/dt*, which are respectively rate of change of voltage and rate of change of current. Now, if the rate of change of voltage is higher and the rate of change of current is higher, the electromagnetic interference will be more. So, they have to be limited to certain extent also to limit the EMI issue.

Further more the amounts of currents are there, more the level of the voltages are there, you are expected to have high *dv/dt* and high *di/dt*. Because in the switching it is going to take place in a short interval of time with higher magnitudes. Let us say if you are changing from *500 V* to *0 V* as compared to changing from *1 kV* to *0 V*, then *1 kV* converter which is having handling those voltages may have higher EMI’s. Of course, it depends on many things. But, that is one of the factors. Now, further we see that, *dv/dt* is going to play a role. With this *dv/dt* there will be associated some currents. What are these going to be those current?

So, if you have some parasitic capacitance, C_p, they will be having the corresponding current

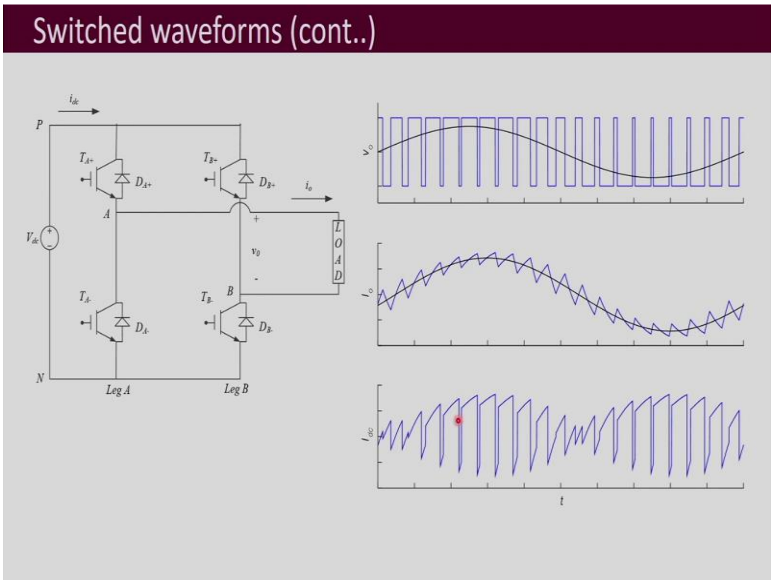
$$C_p \frac{dv}{dt}.$$

Now, these are noise currents. So, this will lead to noise in the currents and if you have further parasitic resistances as R_p and parasitic inductance is L_p, then they will be dropped because of that noise and that will lead to noise in voltage. Similarly, if you have these *di/dt* then this will be

$$L_p \frac{di}{dt}$$

which will lead to noise in the voltage and then further because of that similarly you will be getting noise in current. So, we observe that it is not just about this FFT of the waveform, it is also affected by the parasitics that are present in the circuit. In the different elements the parasitics may be there.

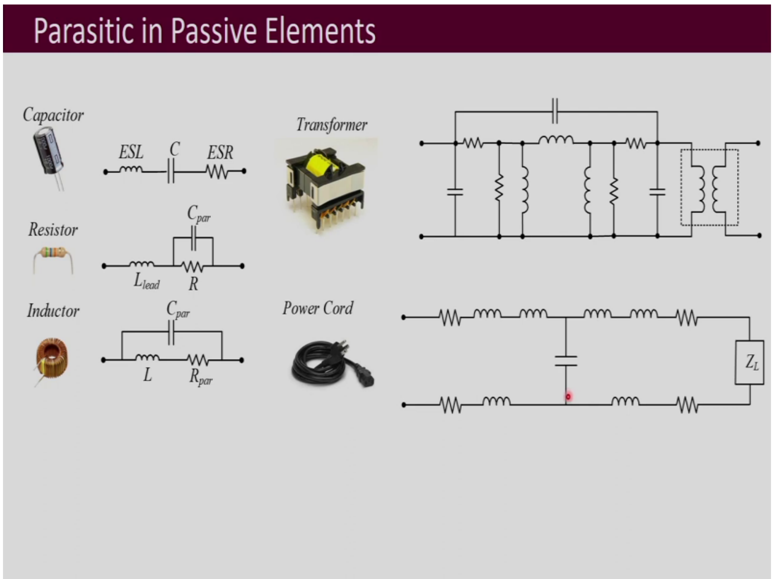
So, because of those parasitics *dv/dt* and *di/dt* will lead to noise in the currents and voltages and then those noises in the currents and voltages are going to affect the converters operation. It can affect the converters operation itself, that means the source and receiver are the same inside the converter or they can be conducted through different cables to other systems and so that will lead to interference in other systems. So, that is the problem of conducted EMI, which will take place because of these noise in voltages and currents.



Now, I gave you a simple example of buck converter. Now, this is true for any power electronic converter. For example, if you have this H-bridge converter, for this H-bridge converter also we had drawn these waveforms before and we had seen that for bipolar PWM this will be the nature of the voltage waveforms at the output, V_o. It will go from $+V_{dc}$ to $-V_{dc}$ and these were the nature of the current waveforms over here and these I_{dc} is the dc bus current and this was a switch current waveform.

So, we observed here again that we have switched voltage waveforms and switch current waveforms. So, this is true for almost power electronic converters for that you will be getting switched voltage waveforms and switched current waveforms at different places and then those can lead to electromagnetic interferences.

Both because of the nature of the waveforms the frequency components are present in it. The *di/dt* and *dv/dt* are associated with the transition in voltages and currents. The effect of parasitics can lead to noise in voltages and currents and that can further lead to the problem of conducted EMI. Then these conducted EMI is these noise voltages in current and they can have their own electromagnetic wave which can also radiate through and can lead to the problem of radiated EMI.



So, let us now look into the different parasitic elements which are present in different components. Those are used in power electronic converters. So, this is a electrolytic capacitor. So, this is the equivalent circuit which shows some of the parasitics. So, these are ESR/ effective series resistance and ESL/ effective series inductance. Now, these lead wires will have their own resistances and inductance. So, more these are higher, the capacitance is deviating from its ideal behaviour and it will become because of the ESR. The capacitor will become lossy more.

Then this is the resistor. Also, we will be having this kind of equivalent circuit where a parasitic capacitance is in parallel with the resistor and this will have these inductance because of the lead wires as well. Then for inductor also it will have the parasitics, then parasitic capacitance and also parasitic resistance *R*.

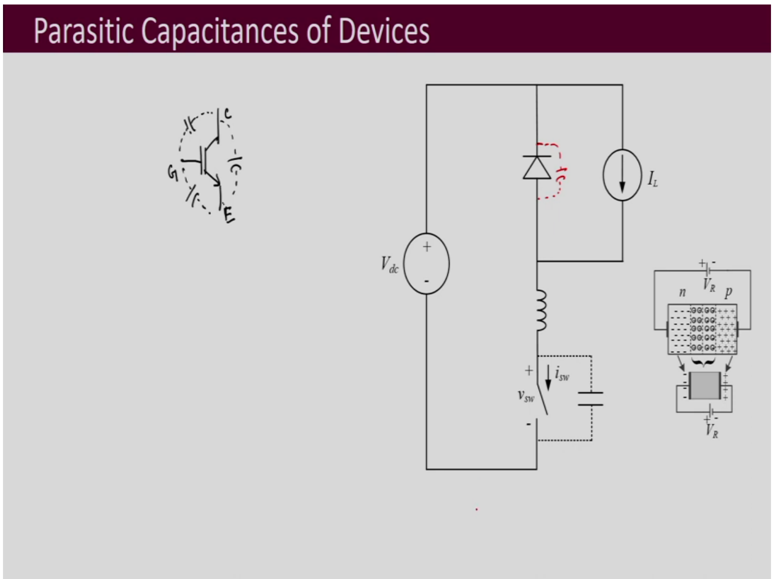
So, we observe here how we analyse the ideal circuit. It is really *RLC*. It is all a combination of every element whether it is *R* or whether it is *L* or whether it is just *C*. They all have all three of them *R*, *L* and *C*.

Then for transformer this is the equivalent circuit, and you might be familiar. There are different equivalent circuits of transformers and you can refer it to primary, secondary. In different ways people show it and it also depends on the frequency at which the transformer is designed and being used. The equivalent circuit also depends on that.

So, here one equivalent circuit is shown, which shows different resistances, inductances and capacitances that are present in the transformer which could be used in particular power electronic application. So, again we say that it is a combination of a RLC network that is actually present inside the transformer. Further, this is present also in these kinds of cords which you might be using or we use these in our everyday life.

So, power cords or cables have to be used for any power electronic converter. For low frequency we just assume that they may be having just some small inductance or some small resistance and in this way we model it. But in reality it is not so. It is actually like a transmission line having all *R*, *L* and *C* present all of them together.

Now, in power electronic converters, the cables or the cords maybe carrying high frequencies and the high frequencies maybe in switched voltages and currents. So, this transmission line model becomes all the way more relevant in that case. So, though that transmission line equivalent circuit can be further terminated by the impedance that will be seen by the cable or the cord at the other end. So, again we see that all elements like *R*, *L* and C are present what we could be just simply thinking as very small resistance or very small inductance.

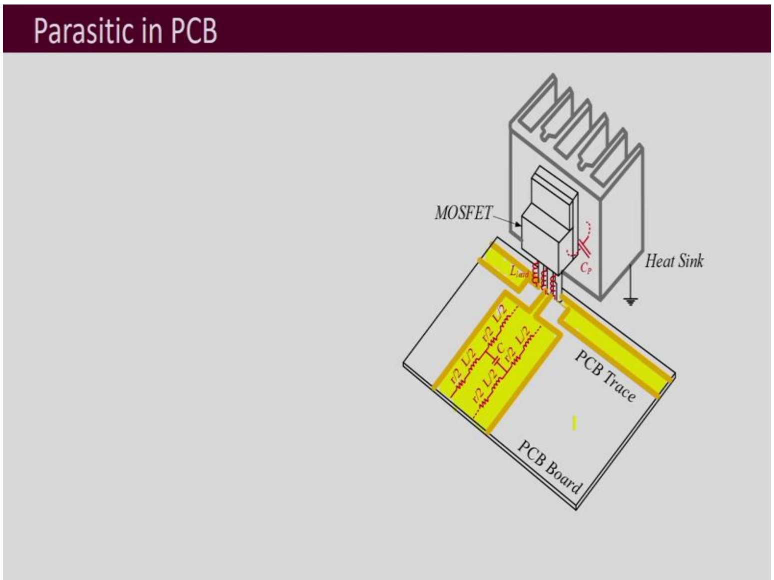


Now, there will be parasitics, which are also present in devices. Now, I had discussed this before also when I discuss devices with you and then we had also seen how they affect the switching performances especially in case of MOSFET and IGBT. So, you might be recalling that we had this in IGBT. Let us say that you have capacitance between all three of the terminals.

So, this is the gate terminal, the collector and emitter. So, between all of these three, there were parasitic capacitances and we also saw that when we discussed snubber design, those parasitic capacitances with the other parasitic inductances may be present in the lead wires or between any two connections and of course, it will always be having some parasitic resistance. They form RLC circuit and then they lead to non-idealities in the waveforms or it will be having ringing in the voltage waveforms.

So, there may be ringing also in the current waveforms during turn off times of switches. So, during turn off times we took into account the ringing in the voltages for these capacitances that are present and those are present in the transistors. Now, further you recall, when I discussed diode then I said that there is a junction capacitance in diodes.

So, this is the diagram shown there. This has this pn junction and this pn junction can be modelled like a capacitor. It shows somewhat like capacitive effect. So, then we can say that there is capacitance in between these two anode and cathode of the diode. Also, that will lead to the problem of electromagnetic interference. Because all these parasitic capacitances are providing additional paths for currents to flow in different positions or in different parts of the circuit. When you are analysing in an ideal circuit, you cannot observe them.



Further in power electronic design you will be using PCB, you will be designing PCBs and on the PCBs all the components like semiconductor devices, inductors and capacitors all will be placed and then you will be putting tracks, PCB traces to connect them and further you may be having sensors and other controllers. Different elements may be present in the PCB.

So, when you look into the PCB, you will observe that this is the MOSFET here which is placed and this is a heat sink which is pasted with the MOSFET. So, this heat sink is usually grounded and between this MOSFET and this heatsink there will be a parasitic capacitance.

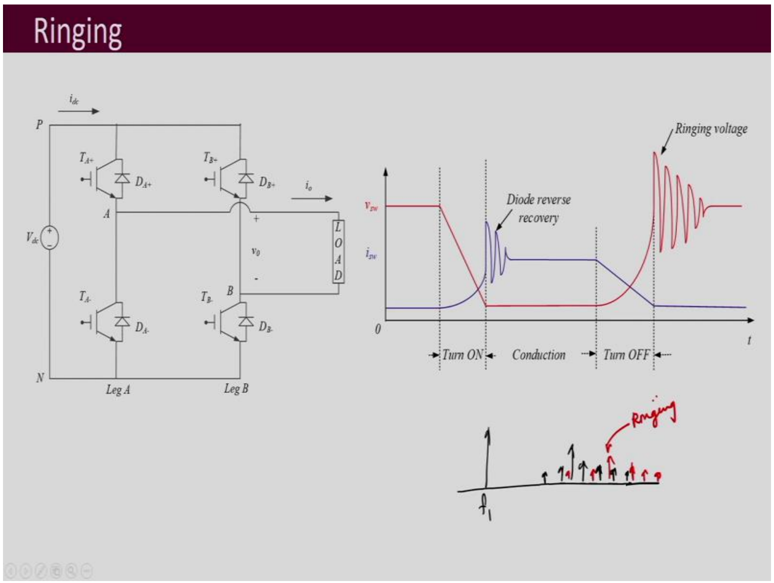
Again note that these are not capacitances which you can physically see. These are getting formed by default if you have any slight potential difference between any two points and you always have a dielectric medium between those two points in it. That may be air or something else. So, that will lead to a capacitive effect.

So, there will be parasitic capacitances between any power semiconductor device being mounted on a heatsink. So, this is a big source of conducted EMI because common mode noise can travel through it which we will be seeing little later. Then these MOSFET's are being connected or soldered to the PCB, and they will have their own inductance. Small parasitic inductance is because of this lead connections, the wires and then the PCB tracks will also have their own parasitics. Let us say this is completely one PCB track, or one large PCB track is very wide.

So, this PCB track can be modelled as a transmission line having all *R*, *L* and *C*. So, it is more relevant as transmission line modelling, because you will be having switched voltages and currents that these traces will be carrying. Similarly, here also if you see this is some PCB trace that may be present and may be connected to the gate, drain and source terminal of the MOSFET, they will be carrying those switch component. Those PCB traces can be modelled as a transmission line. So, we see that the PCB itself is a big source of various parasitics.

So, when we analysed an ideal circuit, this circuit is having no extra *R*, *L* and *C*. When you are going to design the converter or you realize it in the hardware, there are numerous sources which have got different types of parasitics and different types of non-idealities that are going to come into picture.

Then they will lead to different types of noise, that means you expect disruption from the ideal waveform or from the ideal circuit analysis and then those noise will lead to different interference problems. It can be conducted electromagnetic interference or radiated electromagnetic interference. Both may be there.

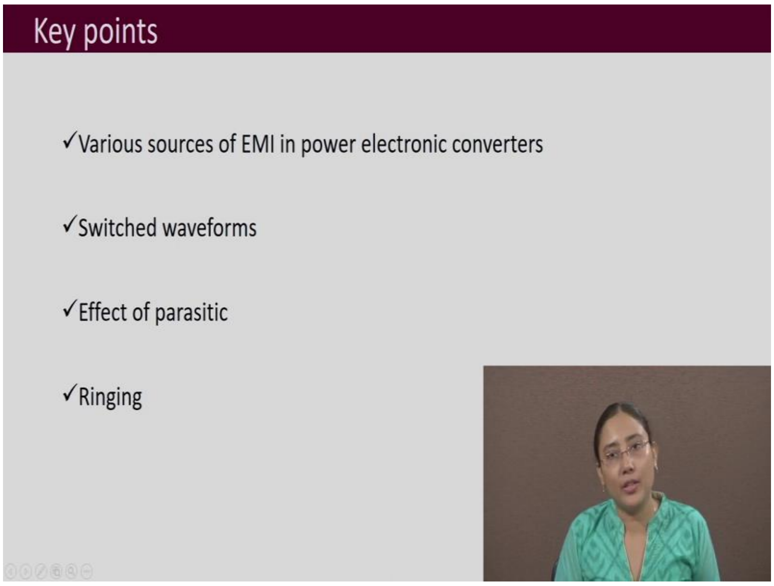


Then next is the ringing phenomenon that takes place again. We had discussed before also when we talked about designing snubbers. There I had shown you this ringing in the voltage while turn off. So, this is a switch voltage waveform across one of the devices and this is a switched current waveforms. This is turn on process and the turn off process.

During turn off what happens? I had explained you before that because all the different parasatics may be present and you are actually forming an RLC circuit, then that transition change will lead to a ringing effect in the voltage and then snubbers were used to limit the peak of this ringing voltage.

Also we had previously discussed this when one transistor is turning on and that is associated with the turn off of the diode. Anytime any IGBT or MOSFET in one leg of a converter is turning on at that time and on the other side diode which was conducting before will be turning off and diode turn off is associated with the reverse recovery current and further we have all these different *RLC* which are present. So, we may be also seeing ringing in the current during turn on.

Now, these ringing again further will have their own spectrum. So, I want to say that this was the fundamental and then you had all these different harmonic contents. When there was no ringing effect that is going to be somewhat different. Let us say you have these ringing which are taking place. So, you will be getting different spectrum because of the ringing effect. So, that also will further contribute to the problem of EMI.



So, the key points of this lecture are that there are various sources of EMI in power electronic converters. The major source is the switched voltage waveforms and there are different types of parasitics that are present all throughout a power electronic converter and it maybe also having the ringing effect. So, all these lead to the problem of EMI in power electronic converters. Thank you.