Design of Power Electronic Converters
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Lecture 14
Switching Characteristics of MOSFET

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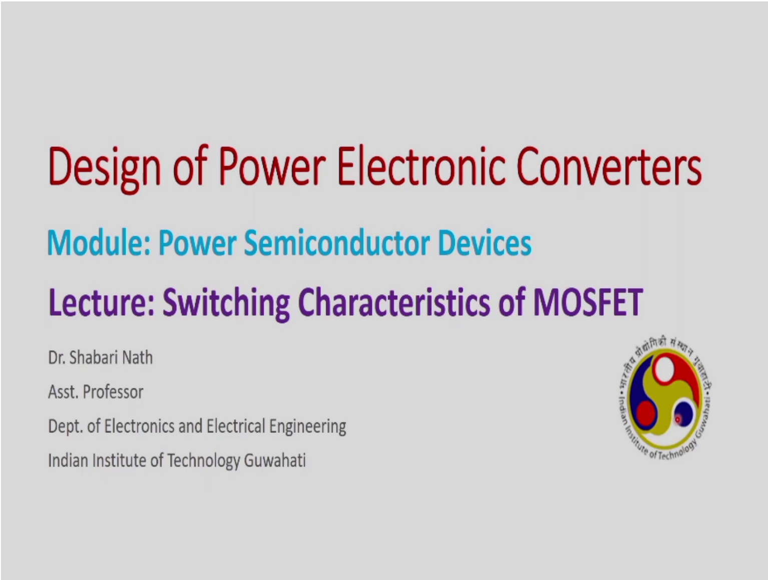

Welcome to the course on Design of Power Electronic Converters. We were in the Module of Power Semiconductor Devices and we had started discussing MOSFETs. Today's lecture, we will be looking into the Switching Characteristics of MOSFETs.

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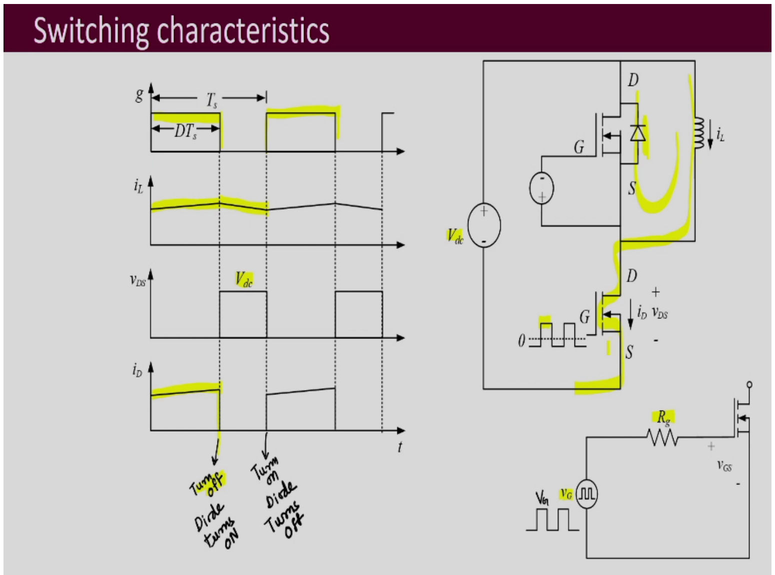

To understand the switching characteristics of MOSFET the type of circuit that can be used is shown here. So, what you see this is the one leg of an H-bridge and here this body diode of the MOSFET is shown explicitly. This is the device under test that means, this is the MOSFET for which we want to study the switching characteristics.

So, if we want to study the switching characteristics of this MOSFET we do not want to allow this MOSFET to conduct. So, this is turned off by giving a negative voltage between the gate and source. Now, the way the circuit functions is that there is a DC supply over here and current flows through this inductor and then it flows through the MOSFET whenever the switch is ON, this gate pulse is high and whenever this gate pulse is low, that means, let us say if you are applying a negative voltage between gate and source.

Then the current will be freewheeling through this diode, because there is already an established current in the circuit. And so, it will be freewheeling through the diode and this is the notation that we are going to use that i_D is the current from drain to source and v_{DS} is the drain to source voltage and v_{GS} is the voltage between gate and source.

Now, to drive it, we can draw an equivalent circuit in this manner that there will be a gate resistor R_g, which will be connected to the gate of the MOSFET and there is a driver which we will be discussing later, which is going to drive this gate to source region. So, this is represented over here with a pulsating voltage source and it is denoted as v_G.

And let us say the voltage that goes to maximum is V_G. Now, the way the waveforms we are going to obtain, so this is gate pulse that is shown here that is the gate pulse which is given over here to the gate to source and then there is the inductor current, there is a slight increase when the MOSFET is ON.

So, the voltage across the inductor at that time is equal to V_{dc} because this MOSFET is ON. So, this we can assume it to be like short because these waveforms are drawn for ideal MOSFET. So, the current toward here will increases slightly when this lower switch is ON, and then when we Turn-OFF this lower MOSFET at that time what will happen is that this diode will start to conduct and so, this MOSFET will be blocking and during this time this diode is freewheeling. So, this inductor current will reduce slightly.

So, this is the inductor current waveform. We will be observing the nature of the inductor current waveform. And what will be the nature of voltage and current waveforms through the MOSFET. So, when the MOSFET is not conducting it is OFF, it is going to block this voltage of V_{dc} and that is what we observe here. And when the MOSFET is conducting at that time it is going to carry the inductor current. So, it is same as this current i_L that is what we observe here. Now, this is the point at which the MOSFET is going to Turn-OFF.

So, this is the Turn-OFF, and this part is the Turn-ON and what we observe is that, here when it is turning OFF the MOSFET, the diode is going to Turn-ON at that time. And here when the MOSFET is turning ON, at that time diode Turn-OFF. So, that also means that that while MOSFET is turning ON, there will be this diode Turn-OFF and so, there will be an influence of this diode Turn-OFF characteristics while the MOSFET is turning ON. Because we have studied this before that diodes while it is turning OFF, it has got the reverse recovery current, reverse recovery charge is associated with it.

And so, that effect we should be expecting to see while the MOSFET is turning On. So, let us look into the switching characteristics of MOSFET now.

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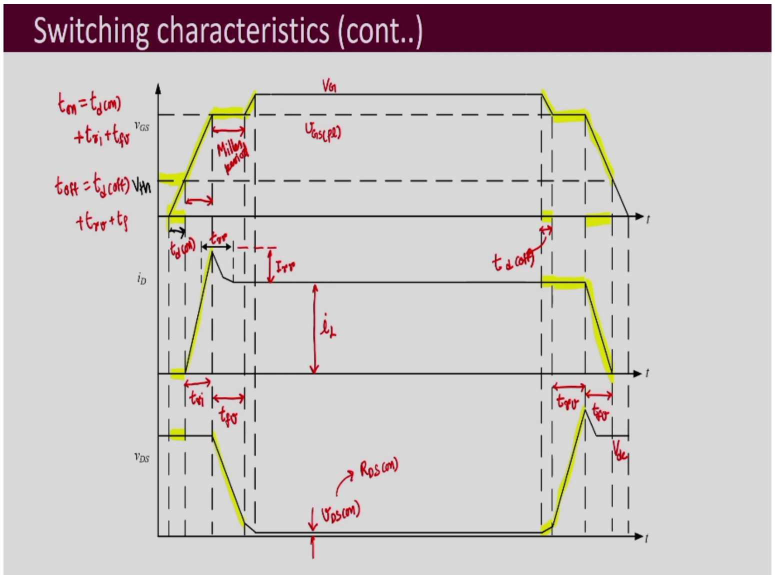

So, this shows the switching characteristics of MOSFET and this is somewhat approximated waveform, do not think that you will be seeing exactly this kind of a theoretical waveform when you do perform the experiments, but more or less this is what is going to happen when you perform the experiment and you switch the MOSFET. So, that is what we will see now.

So, now, let us say v_{GS}, this is going to begin at this point. So, from here to here, this time period, this is v_{GS} voltage gate to source voltage, this is the drain current and this is v_{DS} voltage that is voltage across the MOSFET. So, this is where the gate to source voltage begins to increase.

So, what we observe during this period, neither the current changes nor the voltage changes. So, there is a delay and at that time this v_{GS} increases and it reaches the threshold voltage over here. So, this is the $V_{th\_threshold}$ voltage up till then no current will increase no change will happen. So, there is a delay in the Turn-ON. So, this period we can call it as $t_{d(on)}$.

Next, what happens is this interval when this current starts to increase as the gate to source voltage increases above the threshold voltage and it reaches to this point, which corresponds to Miller voltage or the Miller effect. So, this is given as the name $V_{GS(pl)}$, many times this is denoted like this, it may be denoted in some other way also, but this is basically the Miller voltage.

So, during this time period it is the current which is going to increase and this time period, we can call it as t_{ri}. After that what happens is that voltage tends to decrease and this gate to source voltage over here is remaining constant it is not increasing. One thing you also notice here that before when it is going from threshold to Miller voltage, although the current increased and it actually increased and reached to a value greater than the on state current value which is this, this drain to source voltage did not change at that time.

And now, why is this current higher than what this Turn-ON state MOSFET current is going to be? This is because the diode is also turning OFF at that time and this is associated with the reverse recovery current of the diode. So, this part is reverse recovery current I_{rr}, and this time is t_{rr}, reverse recovery time.

Now, when this Miller period is going ON, at that time, what happens is that there is not much change in current of course, this is basically the reverse recovery current, which is reducing, but there is a huge change in the voltage as goes from the OFF-state voltage to almost very close to the ON state voltage drop.

You can see this part it is almost very close to the on-state voltage drop, and this period is many times denoted as t_{fv}. Further what happens is that whatever is the voltage, which finally is left out that means this $V_{GS(pl)}$ and what is the difference between final voltage the voltage source is providing, which is what we had denoted as V_G that is what is further increased and during that period it is this increase in the voltage that you will be observing in the gate to source voltage and current has reached to the ON state current value before that period and the voltage just finally goes to the on state voltage drop.

So, by this time actually, Miller period is over. This is Miller period. So, by this time the Miller period is over, Turn-ON process is completed. So, this one is V_{DS_on}, the on-state voltage drop and this is very much contributed by the on-state resistance and this part is i_L, inductor current value, during the on state what is going to conduct.

So, on time period then can be written

$$t_{on} = t_{d(on)} + t_{ri} + t_{fv}$$

Then further this continues to remain ON, during this entire time while the gate pulse is there. So, this is ON. So, this just continues. After that let us say now the gate pulse is removed and it starts to Turn-OFF.

So, when it starts to Turn-OFF, let us see what happens. So, initially what happens is that, gate to source voltage goes down from V_G to $V_{GS(pl)}$ i.e. Miller voltage and during that time what you observe is that, that there is a slight increase in the voltage and the current almost remains same.

So, you can see that kind of no change. And so, this is the delay time and we can write it as, this as $t_{d(off)}$. Further, what happens is this Miller period continues during this time and at that time what we observe is that the current does not change, it remains where it is, but the voltage builds up, the voltage builds up and there is a shoot through in the voltage it goes above what it is supposed to block.

So, there is a rise in the voltage and almost no change in the current. So, this time period it can be denoted as t_{rv} rise in the voltage. So, the Miller period gets over by the time after that gate to source voltage starts to reduce and it reaches the threshold voltage.

And during this interval what happens is that the current which starts to come down and almost becomes close to the leakage current or the off state current. And this can be denoted as this interval t_{fi}, the fall in current. And by the time what happens is this shoot through also comes down and it settles close to the blocking voltage.

What the MOSFET is supposed to block, which is equal to V_{dc}. So, what we observe from this is that what happens when it turns off is almost the opposite of what happens when it turns on, when it turns on there is a delay and then first current rises and then voltage decreases. And when it turns off again there is a delay and it is the voltage, which builds up first and then it is the current which comes down. And what we also observe is during these two intervals maximum losses are going to take place because both voltage and current are going to be high together.

Now, what is the reason of this shoot through, this overshoot is basically because of the stray inductances that are present in the circuit stray elements are there, which also lead to shoot through in the voltage, overshoot in the voltage. And turn off time is contributed by this $t_{d(off)}$ and these other two intervals t_{rv} and t_{fi}. So, t_{off} you can write it as

$$t_{off} = t_{d(off)} + t_{rv} + t_{fv}$$

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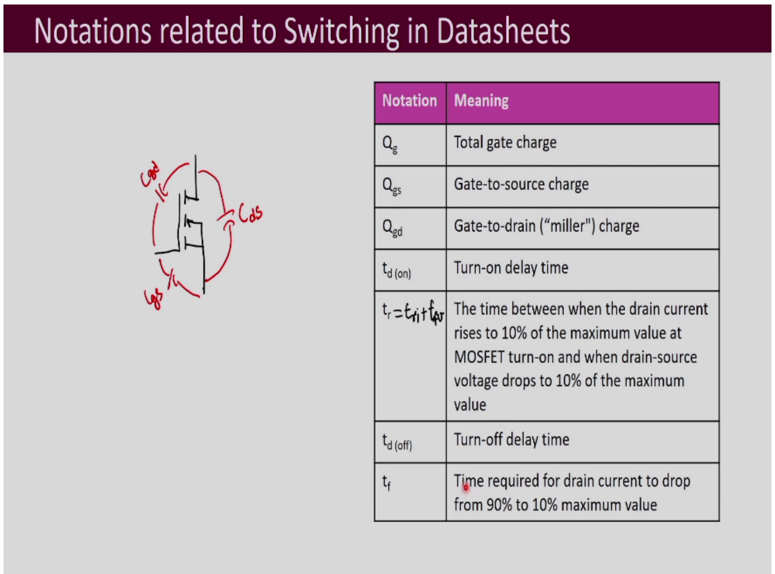

What are the notations which are given in the data sheets related to switching characteristics of the MOSFET? So, total gate charge that is provided for turning ON and turning OFF the MOSFET then, I mean, basically you are charging the 3-capacitances that are involved in it. You may recall this, this we had a look into in last lecture.

So, this is MOSFET and then you have this gate to drain capacitor. Then this one is gate to source capacitor and this part is drain to source capacitor. These three capacitances have to be charged and discharged while the turn-on, and turn-off process are going on. Now, I did not explain here that which capacitance is getting charged and discharged when it is turning on and when it is turning off.

But we will be discussing it later again when we discuss K drive circuits. So, here I just wanted to tell you that what is the nature of the turn-on and turn-off waveforms? So, as these capacitances are turned on, I mean basically they are charged and discharged there of course, it will be a charge associated with it.

And so, those are given in the data sheets as total gate charge, then gate to source charge, which is associated with this capacitance c_{gs}. And then gate to drain charge, which is the Miller charge and that is c_{gd} then this turn-on delay time, $t_{d(on)}$ this we just saw. So, that is what is provided in the datasheet many times.

Then t_r is also specified and the way many of the application notes they define it as the time between when the drain current rises to 10% of the maximum value at MOSFET turn-on, and when drain to source voltage drops to 10% of maximum value. So, that means this t_r is sum of that we just saw that t_{ri} and t_{fv}.

Then other times which are specified in the data sheets is your $t_{d(off)}$ turn-off delay time, that is also we just saw and t_f fall time, which is the time required for drain current to drop from 90% to 10% of maximum value. This also we just saw in the switching characteristics. So, these are mostly notations which you will find in the data sheet and we just discussed it now.

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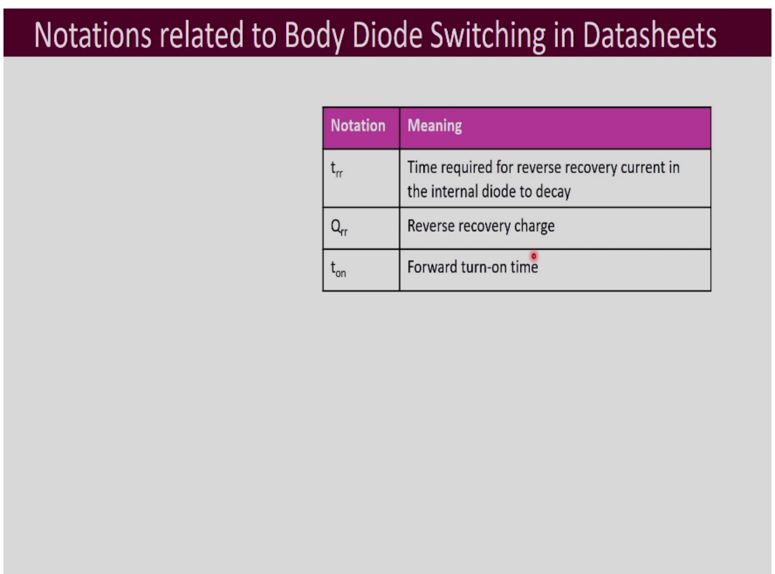

Notation	Meaning
t_{rr}	Time required for reverse recovery current in the internal diode to decay
Q_{rr}	Reverse recovery charge
t_{on}	Forward turn-on time

Then notations related to body diode, reverse recovery time of the diode and Q_{rr}, reverse recovery charge associated with the diode and the forward turn-on time. This sometimes may not be given; some data sheets will also be giving you the maximum reverse recovery current and forward turn-on time also. But most of the time as I had told you before also it is the turn-off time which dominates for diodes.

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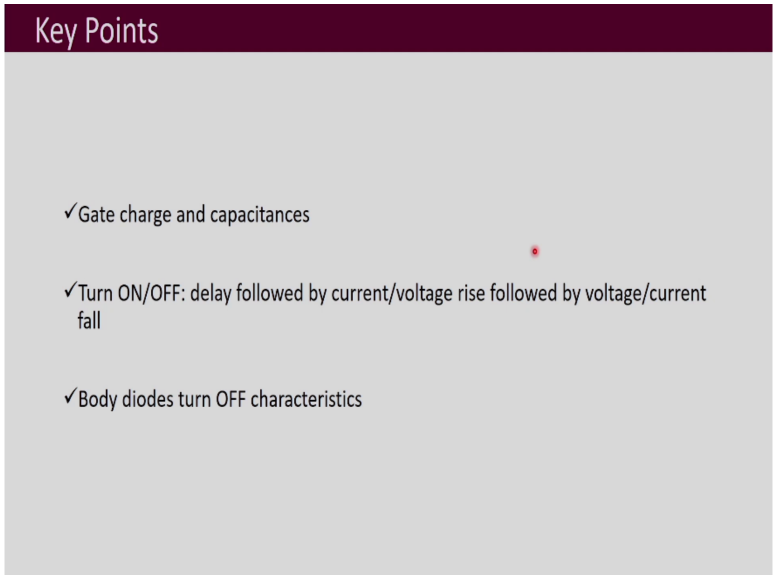

So, what are the key points of this lecture? So, there are gate charges and associated capacitances which play the role in the turn-on and turn-off process of the MOSFET. And the usual sequence is that first there will be a delay, then there will be a rise in current and there will be after that fall in voltage and exactly the opposite sequence follows when the MOSFET gets turned off. And the body diodes turn-off characteristics affects the turn-on of the MOSFET. Thank you.