Design of Power Electronic Converters

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Module Snubber Design

Lecture – 37

RCD Snubbers - II

Welcome to the course on Design of Power Electronic Converters. We had been discussing the module snubber design and we had seen the snubber designs for RC snubbers, then we started with the analysis of RCD snubbers. And in that we saw that the we can divide it into three types, one is normal snubber, large snubber and small snubber. We had derived equations for normal snubber in last lecture. Now, this lecture we will be continuing for the analysis for large snubber and small snubber.

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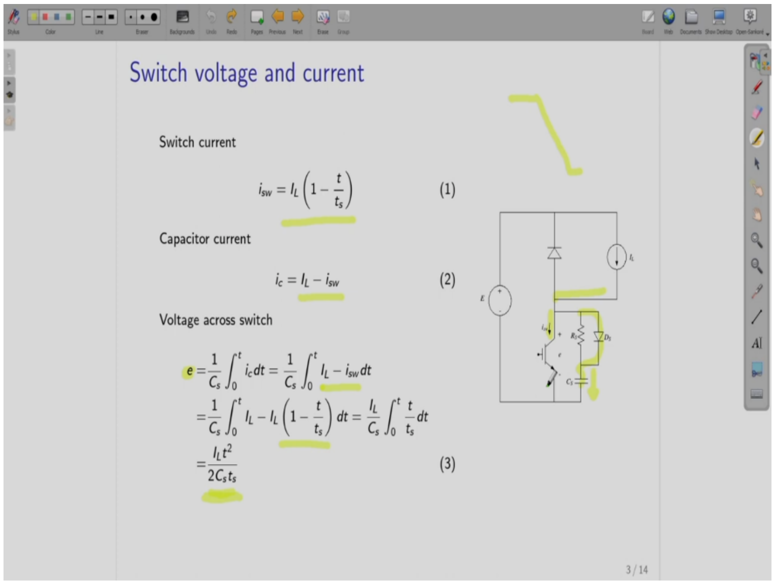


Switch voltage and current

Switch current

$$i_{sw} = I_L\left(1-\frac{t}{t_s}\right) \qquad (1)$$

Capacitor current

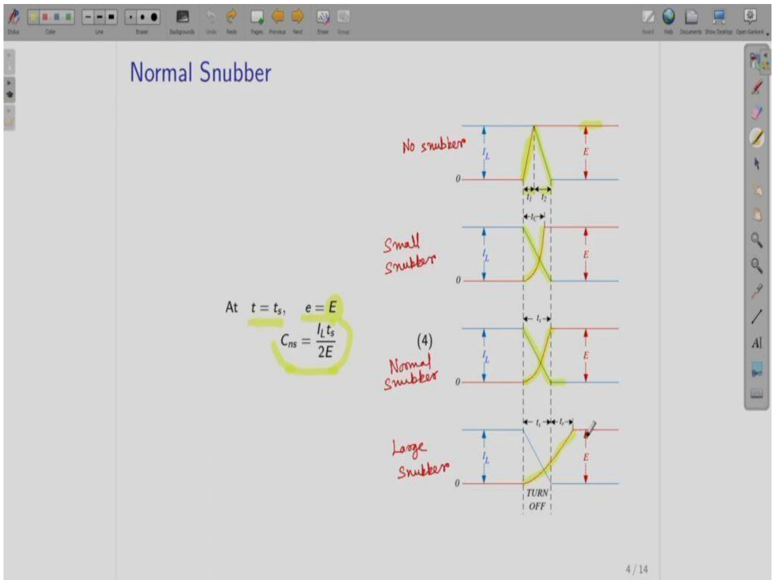
$$i_c = I_L - i_{sw} \qquad (2)$$

Voltage across switch

$$e = \frac{1}{C_s}\int_0^t i_c dt = \frac{1}{C_s}\int_0^t I_L - i_{sw} dt$$

$$= \frac{1}{C_s}\int_0^t I_L - I_L\left(1-\frac{t}{t_s}\right) dt = \frac{I_L}{C_s}\int_0^t \frac{t}{t_s} dt$$

$$= \frac{I_L t^2}{2C_s t_s} \qquad (3)$$



Normal Snubber

At $t = t_s$, $e = E$

$$C_{ns} = \frac{I_L t_s}{2E} \quad (4)$$

So, to do the analysis, so we first wrote down these simple equations for currents and voltages. For this device, voltage e which is basically the voltage across this capacitor Cs, and then we had also written expression for this switch current. Then, we divided it into three parts, small snubber, normal snubber, and large snubber. And for normal snubber case, we had noted down that this snubber can be the capacitance can be calculated as this

$$C_{ns} = \frac{I_L t_s}{2E}$$

where IL is the load current,, ts is the turn off time, and E is the blocking voltage.

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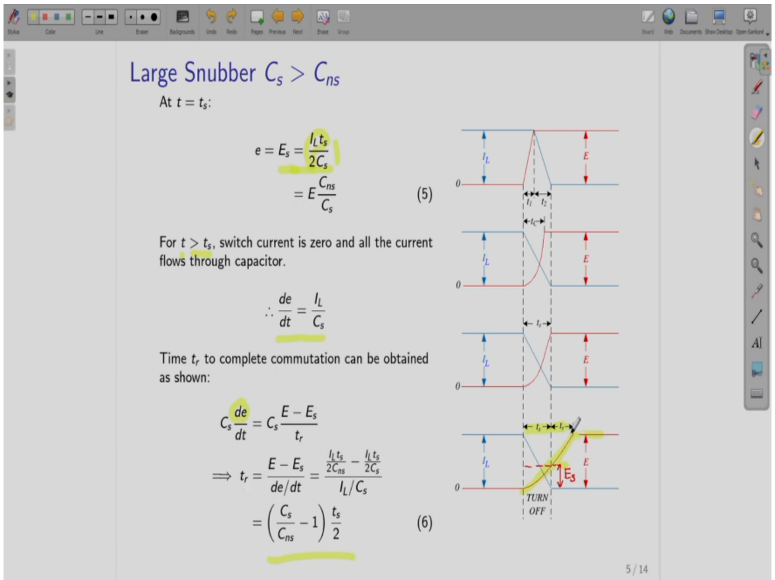


Large Snubber $C_s > C_{ns}$

At $t = t_s$:

$$e = E_s = \frac{I_L t_s}{2C_s} = E\frac{C_{ns}}{C_s} \tag{5}$$

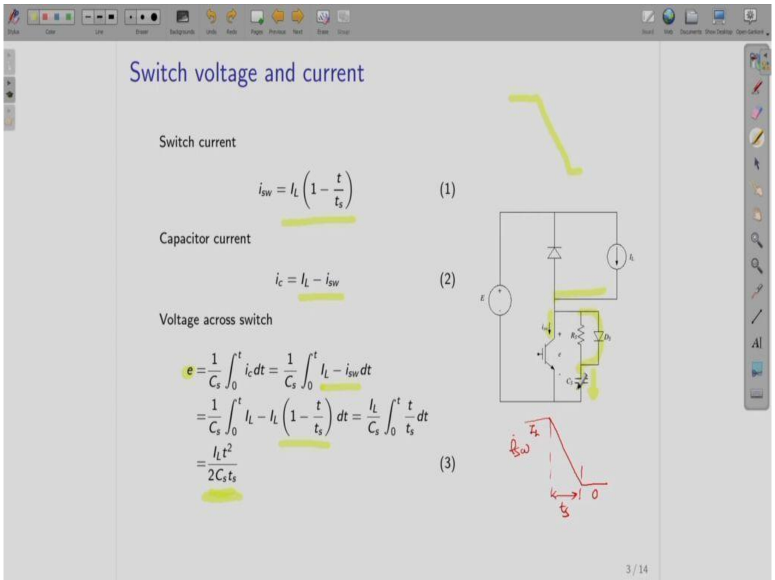
For $t > t_s$, switch current is zero and all the current flows through capacitor.

$$\therefore \frac{de}{dt} = \frac{I_L}{C_s}$$

Time t_r to complete commutation can be obtained as shown:

$$C_s\frac{de}{dt} = C_s\frac{E - E_s}{t_r}$$

$$\implies t_r = \frac{E - E_s}{de/dt} = \frac{\frac{I_L t_s}{2C_{ns}} - \frac{I_L t_s}{2C_s}}{I_L/C_s} = \left(\frac{C_s}{C_{ns}} - 1\right)\frac{t_s}{2} \tag{6}$$



Switch voltage and current

Switch current

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Capacitor current

$$i_c = I_L - i_{sw} \qquad (2)$$

Voltage across switch

$$\begin{aligned} e &= \frac{1}{C_s}\int_0^t i_c dt = \frac{1}{C_s}\int_0^t I_L - i_{sw} dt \\ &= \frac{1}{C_s}\int_0^t I_L - I_L\left(1 - \frac{t}{t_s}\right) dt = \frac{I_L}{C_s}\int_0^t \frac{t}{t_s} dt \\ &= \frac{I_L t^2}{2C_s t_s} \qquad (3) \end{aligned}$$

Now, let us do further and do the analysis for large snubber. Large snubber means this case where your capacitor voltage builds up slowly that means it is large enough, and it reaches to this blocking voltage at a time later than this turn off time ts. And let us say it reaches later by that time by an additional time of tr.

So, at the time ts, let us say that this voltage is equal to Es. So, now when you want to write equations using the previous equation, so you can write this Es at time ts

$$e = E_s = \frac{I_L t_s}{2C_s}$$

$$= E\frac{C_{ns}}{C_s} \qquad (5)$$

Cns is the normal snubber capacitance.

And for this time interval which is t greater than ts, what will happen is that the switch current has become 0 in that case. So, what we are telling is that after the time period t is this current your isw, this is gone from your IL to the value 0. So, your this switch current is 0 now, and so all this current is going to flow through the capacitor Cs.

So, in that case your de by dt the rate of change of the voltage will be equal to

$$\frac{de}{dt} = \frac{I_L}{C_s}$$

And the time tr to complete this commutation process can be obtained as

$$C_s \frac{de}{dt} = C_s \frac{E - E_s}{t_r} \quad .$$

Now tr is equal to,

$$C_s \frac{de}{dt} = C_s \frac{E - E_s}{t_r}$$

and you substitute for ease, you substitute for Es using the previously derived equations. And then when you reduce it,

$$\Rightarrow t_r = \frac{E - E_s}{de/dt} = \frac{\frac{I_L t_s}{2C_{ns}} - \frac{I_L t_s}{2C_s}}{I_L / C_s}$$

$$t_r = \left(\frac{C_s}{C_{ns}} - 1 \right) \frac{t_s}{2}$$

(6)

this is what you are going to get. And Cs by Cns minus 1 into ts by 2 is the the extra time it needs to complete the commutation.

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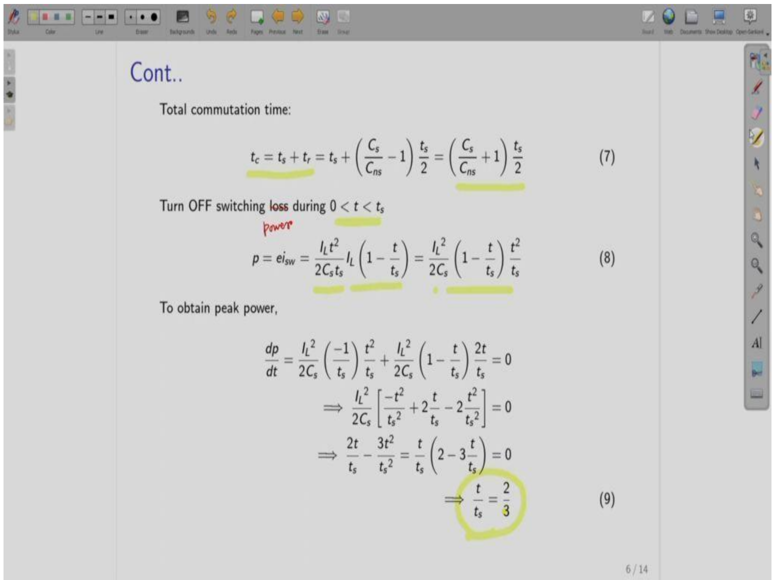

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Total commutation time:

$$t_c = t_s + t_r = t_s + \left(\frac{C_s}{C_{ns}} - 1\right)\frac{t_s}{2} = \left(\frac{C_s}{C_{ns}} + 1\right)\frac{t_s}{2} \qquad (7)$$

Turn OFF switching ~~loss~~ power during $0 < t < t_s$

$$p = ei_{sw} = \frac{I_L t^2}{2C_s t_s} I_L \left(1 - \frac{t}{t_s}\right) = \frac{I_L^2}{2C_s}\left(1 - \frac{t}{t_s}\right)\frac{t^2}{t_s} \qquad (8)$$

To obtain peak power,

$$\frac{dp}{dt} = \frac{I_L^2}{2C_s}\left(\frac{-1}{t_s}\right)\frac{t^2}{t_s} + \frac{I_L^2}{2C_s}\left(1 - \frac{t}{t_s}\right)\frac{2t}{t_s} = 0$$

$$\implies \frac{I_L^2}{2C_s}\left[\frac{-t^2}{t_s^2} + 2\frac{t}{t_s} - 2\frac{t^2}{t_s^2}\right] = 0$$

$$\implies \frac{2t}{t_s} - \frac{3t^2}{t_s^2} = \frac{t}{t_s}\left(2 - 3\frac{t}{t_s}\right) = 0$$

$$\implies \frac{t}{t_s} = \frac{2}{3} \qquad (9)$$

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So, the total commutation time will be

$$t_c = t_s + t_r = t_s + \left(\frac{C_s}{C_{ns}} - 1\right)\frac{t_s}{2} = \left(\frac{C_s}{C_{ns}} + 1\right)\frac{t_s}{2} \qquad (7)$$

Now, the switching power loss you can say that during this time period 0 to ts.

So, this is your p equal

$$p = ei_{sw} = \frac{I_L t^2}{2C_s t_s} I_L \left(1 - \frac{t}{t_s}\right) = \frac{I_L^2}{2C_s}\left(1 - \frac{t}{t_s}\right)\frac{t^2}{t_s} \qquad (8)$$

And now we want to obtain the peak power. So, if you want to obtain the peak power that means you have to differentiate it, you have to obtain the maxima, and you differentiate and equate it to 0. So, we do that exercise and we obtain,

$$\frac{dp}{dt} = \frac{I_L^2}{2C_s}\left(\frac{-1}{t_s}\right)\frac{t^2}{t_s} + \frac{I_L^2}{2C_s}\left(1 - \frac{t}{t_s}\right)\frac{2t}{t_s} = 0$$

$$\Rightarrow \frac{t}{t_s} = \frac{2}{3} \qquad (9)$$

So, at this time t by ts equal to 2 by 3 is your this power, this switching power is going to become maximum. Now, you whether it is a maxima or minima, you can check it for yourself, do the double differentiation and then you can check it.

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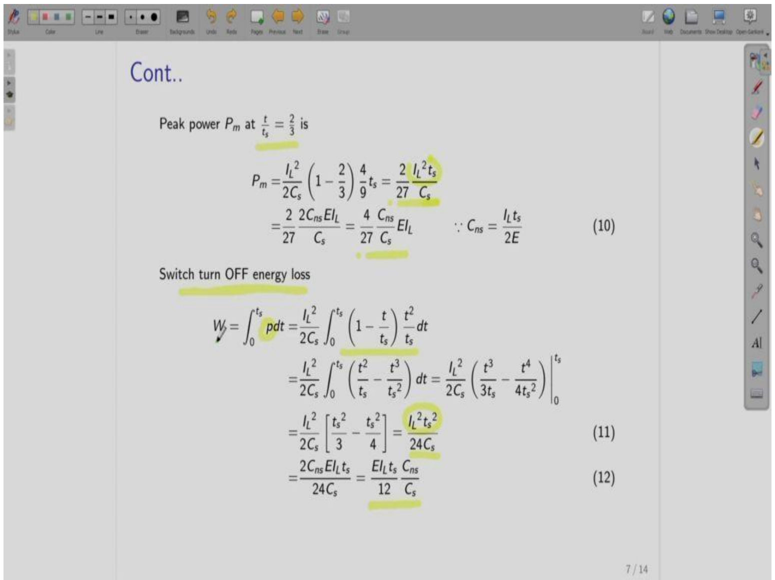

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Peak power P_m at $\frac{t}{t_s} = \frac{2}{3}$ is

$$P_m = \frac{I_L^2}{2C_s}\left(1 - \frac{2}{3}\right)\frac{4}{9}t_s = \frac{2}{27}\frac{I_L^2 t_s}{C_s}$$

$$= \frac{2}{27}\frac{2C_{ns}EI_L}{C_s} = \frac{4}{27}\frac{C_{ns}}{C_s}EI_L \qquad \because C_{ns} = \frac{I_L t_s}{2E} \tag{10}$$

Switch turn OFF energy loss

$$W = \int_0^{t_s} pdt = \frac{I_L^2}{2C_s}\int_0^{t_s}\left(1 - \frac{t}{t_s}\right)\frac{t^2}{t_s}dt$$

$$= \frac{I_L^2}{2C_s}\int_0^{t_s}\left(\frac{t^2}{t_s} - \frac{t^3}{t_s^2}\right)dt = \frac{I_L^2}{2C_s}\left(\frac{t^3}{3t_s} - \frac{t^4}{4t_s^2}\right)\Big|_0^{t_s}$$

$$= \frac{I_L^2}{2C_s}\left[\frac{t_s^2}{3} - \frac{t_s^2}{4}\right] = \frac{I_L^2 t_s^2}{24C_s} \tag{11}$$

$$= \frac{2C_{ns}EI_L t_s}{24C_s} = \frac{EI_L t_s}{12}\frac{C_{ns}}{C_s} \tag{12}$$

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Further, if you substitute this t by ts equal to 2 by 3 in the power expression. So, if you do it and then reduce it, so, this is what you will be getting

$$P_m = \frac{2}{27}\frac{I_L^2 t_s}{2E}$$

Now, we want to reduce everything in terms of that normal snubber capacitance value. So, you substitute for these IL square ts from the previously derived equation for Cns, and then when you reduce it, this is what you will be getting

$$P_m = \frac{4}{27}\frac{C_{ns}}{C_s}EI_L$$

(10)

So, now if we want to turn off energy loss in the switch that means in only in the device. So, then that will be integration of this power from this time 0 to ts, during the turn off time 0 to ts.

So, you write down the expression for p that we just derived and then you integrate it, and you solve it. So, and further when you reduce this is what you will be getting

$$W = \int_0^{t_s} pdt = \frac{I_L^2 t_s^2}{24C_s} \tag{11}$$

Again, we do not like this term, so, we want to give get everything in terms of this normal capacitance Cns. So, you do those adjustments and substitutions. This is what you will be getting

$$W = \frac{EI_L t_s}{12} \frac{C_{ns}}{C_s}$$

(12)

this is the device loss that is taking place during the time ts.

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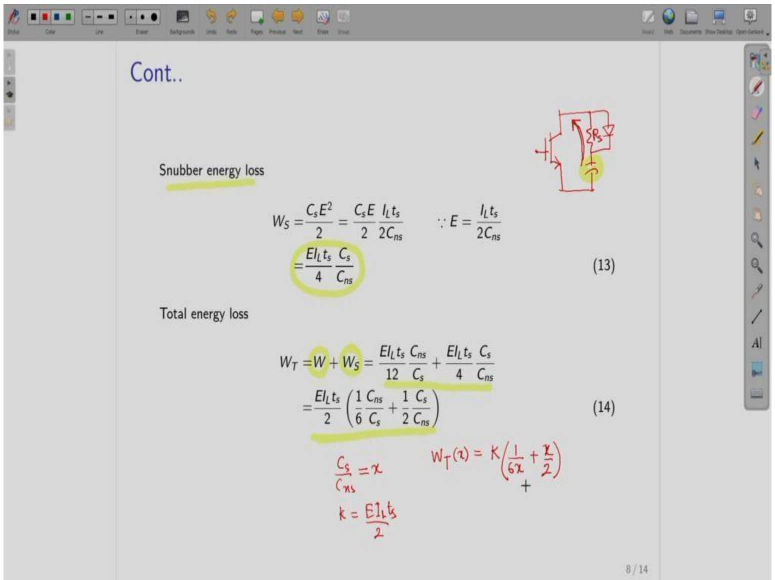

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Snubber energy loss

$$W_S = \frac{C_s E^2}{2} = \frac{C_s E}{2} \frac{I_L t_s}{2C_{ns}} \qquad \because E = \frac{I_L t_s}{2C_{ns}}$$

$$= \frac{E I_L t_s}{4} \frac{C_s}{C_{ns}} \tag{13}$$

Total energy loss

$$W_T = W + W_S = \frac{E I_L t_s}{12} \frac{C_{ns}}{C_s} + \frac{E I_L t_s}{4} \frac{C_s}{C_{ns}}$$

$$= \frac{E I_L t_s}{2} \left(\frac{1}{6} \frac{C_{ns}}{C_s} + \frac{1}{2} \frac{C_s}{C_{ns}} \right) \tag{14}$$

$\frac{C_s}{C_{ns}} = x$

$W_T(x) = K\left(\frac{1}{6x} + \frac{x}{2}\right)$

$k = \frac{E I_L t_s}{2}$

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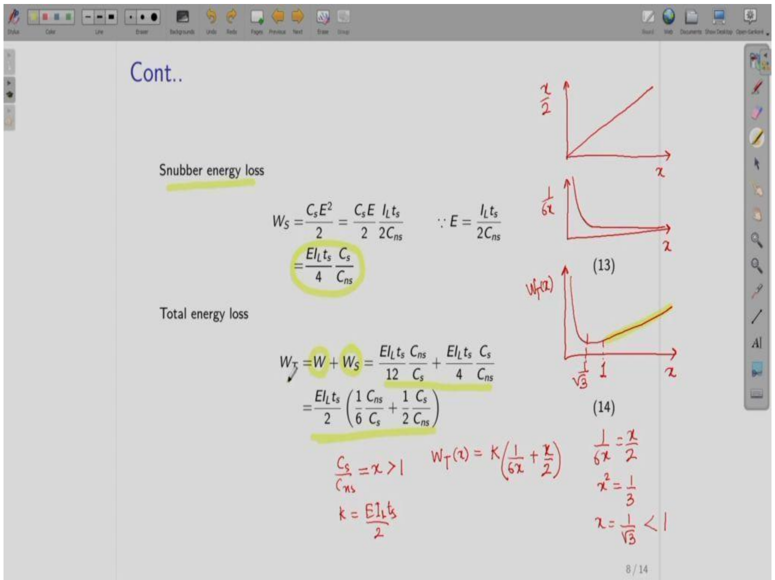

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Snubber energy loss

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Total energy loss

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$$= \frac{E I_L t_s}{2} \left(\frac{1}{6} \frac{C_{ns}}{C_s} + \frac{1}{2} \frac{C_s}{C_{ns}} \right) \tag{14}$$

$\frac{C_s}{C_{ns}} = x > 1$

$W_T(x) = K\left(\frac{1}{6x} + \frac{x}{2}\right)$

$k = \frac{E I_L t_s}{2}$

$\frac{1}{6x} = \frac{x}{2}$

$x^2 = \frac{1}{3}$

$x = \frac{1}{\sqrt{3}} < 1$

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Now, we obtain the device loss. Now, what about this snubber loss? In this snubber loss, there is some loss going to take place. Now, what do we mean by snubber loss here? So, this is your device and then this is the RC and with that this diode is connected. So, whatever is the energy that gets stored in this capacitor that same energy is going to get dissipated in the resistor Rs later on. So, whatever is the stored energy that is actually a loss. So, we just can obtain this snubber energy loss as half of Cs into E square, so you substitute for E as equal to IL Ts by 2 Cns.

And then what you obtain is this expression

$$W_s = \frac{EI_L t_s}{4} \frac{C_s}{C_{ns}} \tag{13}$$

Now, the total energy loss will be the sum of the device loss means your switch loss plus this snubber loss. So, you write down the two expressions that we just obtained. And we can write that in this term

$$W_T = W + W_s = \frac{EI_L t_s}{12} \frac{C_{ns}}{C_s} + \frac{EI_L t_s}{4} \frac{C_s}{C_{ns}}$$

$$W_T = \frac{EI_L t_s}{4} \left(\frac{1}{6} \frac{C_s}{C_{ns}} + \frac{1}{2} \frac{C_s}{C_{ns}} \right)$$

Now, this let us say that your this is Cs by Cns, let us say with this is equal to x. So, this then this WT can be written as a function of x,

$$\frac{C_s}{C_{ns}} = x, \qquad K = \frac{EI_L t_s}{2}, \qquad W_T(x) = K\left(\frac{1}{6x} + \frac{x}{2} \right)$$

Now, let us see what would be the nature of the graph of this equation.

So, if you plot the first one, that is x by 2, so x by 2 graph will be something like this with respect to x. And the nature of the graph of a 1 by 6x with respect to x will be something like this. And so, if we have to then plot this WT x total loss with respect to x, then this nature of the graph will be that initially it will be dominated.

The graph will be dominated for lower values of x by this 1 by 6x. And then later on as x increases, this is what is going to dominate the WT x value, this x by 2 curve, so accordingly, you expect the nature of the graph to be something like this. And then what point is the minimum going to occur? That is going to occur basically, if you want you can differentiate and equate to 0 and also find out.

You can see that when these two are actually equal, so when

$$\frac{1}{6x} = \frac{x}{2}, \qquad x^2 = \frac{1}{3}$$

so x will be equal to

$$x = \frac{1}{\sqrt{3}} \qquad < 1$$

Now, this x is something less than 1, so, that means this minima occurs at 1 by root 3. And here what we are interested in, since this is a large snubber, we our values of x which for which we are doing the analysis is x is greater than 1.

So, for x greater than 1, what happens is what you see is that this is just an increasing function. So, even if you search for a minima, you are not going to get a minima for x greater than 1, it is continuously increasing function. So, that is why we are not going to search for this large snubber of minimum value for your WT.

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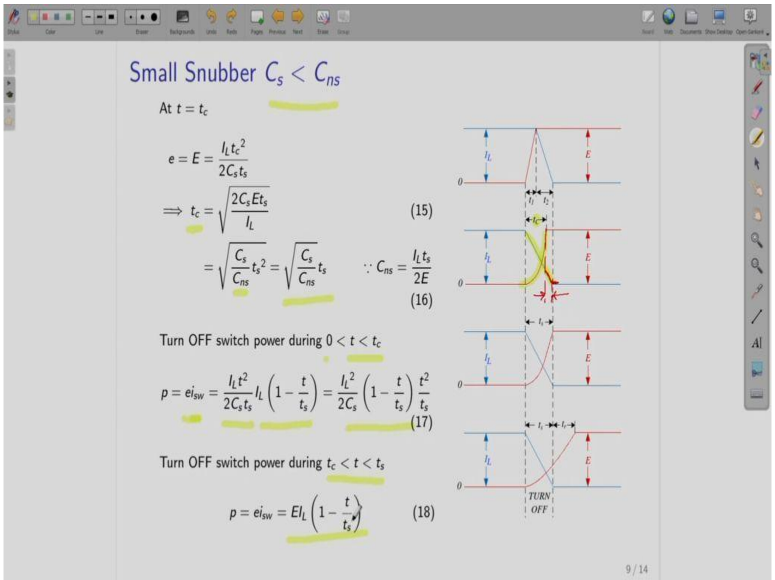

Small Snubber $C_s < C_{ns}$

At $t = t_c$

$$e = E = \frac{I_L t_c^2}{2C_s t_s}$$

$$\implies t_c = \sqrt{\frac{2C_s E t_s}{I_L}} \qquad (15)$$

$$= \sqrt{\frac{C_s}{C_{ns}} t_s^2} = \sqrt{\frac{C_s}{C_{ns}}} t_s \qquad \because C_{ns} = \frac{I_L t_s}{2E} \qquad (16)$$

Turn OFF switch power during $0 < t < t_c$

$$p = ei_{sw} = \frac{I_L t^2}{2C_s t_s} I_L \left(1 - \frac{t}{t_s}\right) = \frac{I_L^2}{2C_s}\left(1 - \frac{t}{t_s}\right)\frac{t^2}{t_s} \qquad (17)$$

Turn OFF switch power during $t_c < t < t_s$

$$p = ei_{sw} = EI_L \left(1 - \frac{t}{t_s}\right) \qquad (18)$$

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Now, let us do the analysis for small snubber. So, small snubber means your Cs, the snubber capacitance is less than your normal snubber capacitance. So, this is the graph that we are going to take up, then that it gets charged the capacitor gets charged before this turn off period is over. So, before the current reaches to 0, before that the voltage has already built up to the blocking voltage.

So, let us say that happens at the time which we call it as the tc time time for your voltage to build up. So, that is there at that time this is the equation that you will be obtaining

$$e = E = \frac{I_L t_c^{\,2}}{2C_s t_s}$$

So, from here if you want to write down the expression for tc, tc could be written as

$$t_c = \sqrt{\frac{2C_s E t_s}{I_L}} \qquad (15)$$

Now, we want to get rid of some of the terms here in terms of Cns, normal snubber capacitance.

$$t_c = \sqrt{\frac{C_s}{C_{ns}}} t_s \qquad (16)$$

So, the turn off switch power during the interval 0 to tc that will be

$$p = ei_{sw} = \frac{I_L t_c^2}{2C_s t_s} I_L \left(1 - \frac{t}{t_s}\right) = \frac{I_L}{2C_s t_s}\left(1 - \frac{t}{t_s}\right)\frac{t^2}{t_s}$$

(17)

multiplication of E into isw. So, write down the expression for E, write down expression for isw, and from there this is what we get. And this is the same as that we had expression that we had obtained for you large snubber, for this time interval 0 to tc.

Then, for your Turn OFF switch power during this time interval tc to ts, so we are now further when we go down to this interval, so here this is between tc to ts. What we see is that the current is reducing and it is becoming 0, while the voltage is a capital E. So, then you can write down the equation.

$$p = ei_{sw} = EI_L\left(1 - \frac{t}{t_s}\right)$$

(18)

that is what will be the expression for power.

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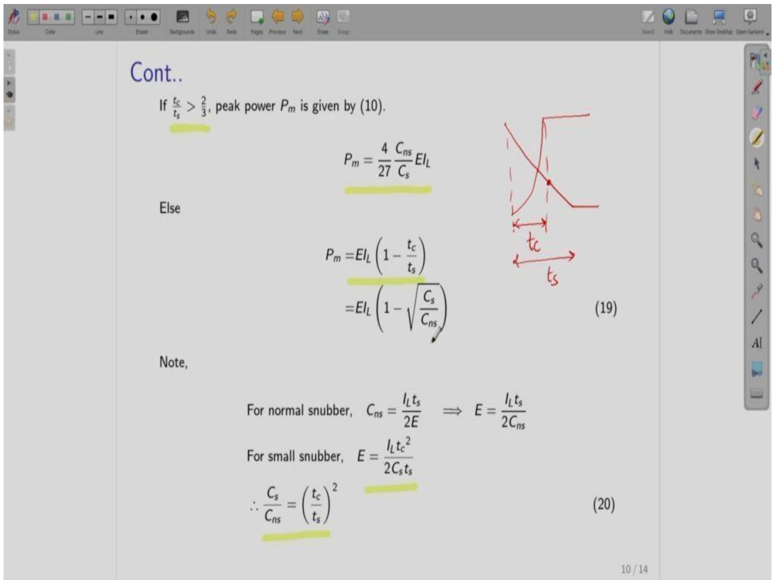

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If $\frac{t_c}{t_s} > \frac{2}{3}$, peak power P_m is given by (10).

$$P_m = \frac{4}{27}\frac{C_{ns}}{C_s}EI_L$$

Else

$$\begin{aligned} P_m &= EI_L\left(1 - \frac{t_c}{t_s}\right) \\ &= EI_L\left(1 - \sqrt{\frac{C_s}{C_{ns}}}\right) \end{aligned} \quad (19)$$

Note,

For normal snubber, $C_{ns} = \frac{I_L t_s}{2E} \implies E = \frac{I_L t_s}{2C_{ns}}$

For small snubber, $E = \frac{I_L t_c^2}{2C_s t_s}$

$$\therefore \frac{C_s}{C_{ns}} = \left(\frac{t_c}{t_s}\right)^2 \quad (20)$$

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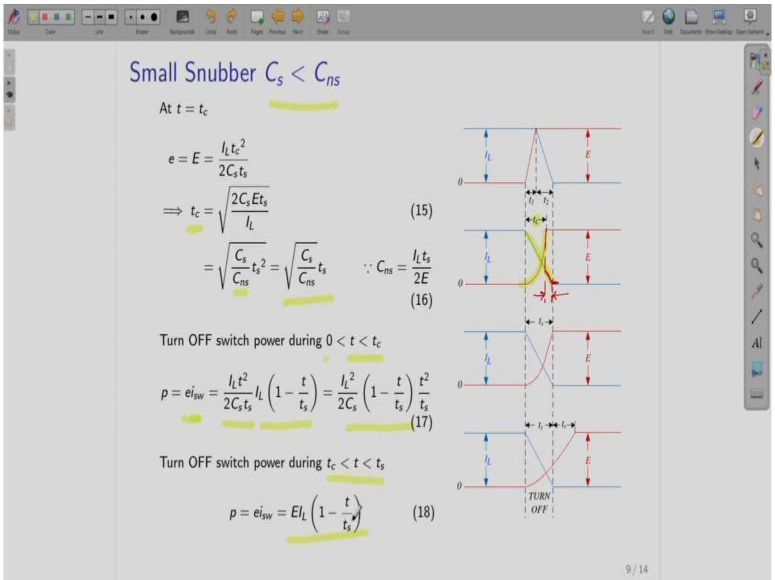

Small Snubber $C_s < C_{ns}$

At $t = t_c$

$$e = E = \frac{I_L t_c^2}{2C_s t_s}$$

$$\implies t_c = \sqrt{\frac{2C_s E t_s}{I_L}} \quad (15)$$

$$= \sqrt{\frac{C_s}{C_{ns}}t_s^2} = \sqrt{\frac{C_s}{C_{ns}}}t_s \qquad \because C_{ns} = \frac{I_L t_s}{2E} \quad (16)$$

Turn OFF switch power during $0 < t < t_c$

$$p = ei_{sw} = \frac{I_L t^2}{2C_s t_s}I_L\left(1 - \frac{t}{t_s}\right) = \frac{I_L^2}{2C_s}\left(1 - \frac{t}{t_s}\right)\frac{t^2}{t_s} \quad (17)$$

Turn OFF switch power during $t_c < t < t_s$

$$p = ei_{sw} = EI_L\left(1 - \frac{t}{t_s}\right) \quad (18)$$

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So, if we want to obtain the peak power Pm, then if tc by ts is greater than 2 by 3, so it will be the same expression that we have obtained for your large snubber case. Because, what we found there for large snubber case that the peak occurs at t by ts equal to 2 by 3, and here we have the same expression is the large snubber. So, if tc by ts is greater than 2 by 3. So, if this expression has its peak at a before that, so the peak power expression will be the same as the large snubber. So, that is what it will be part of this is not so. If let us say this is less than 2 by 3, then this peak will occur at time tc.

Now, why is it going to occur at time tc? Because this is your voltage E which is building up at time your tc. And this is the current to which falls down like this and that happens for this time period ts. So, from here to here, your this voltage is fixed, now the current is reducing. So, your multiplication will be maximum over at this tc point only, beyond that the current value decreases, so the p value is also going to decrease. So, Pm will be equal to

$$p_m = EI_L\left(1-\frac{t_c}{t_s}\right)$$

So, you can substitute for tc by ts in terms of Cs by Cns. And how do we get it? You can note down this that Cns is equal to this, we have previously derived. And for small snubber this also we have previously written. You equate these two terms, this is what you will be getting Cs by Cns equal to tc by ts whole square (see the screenshot). So, from there you can write down this

$$p_m = EI_L\left(1-\sqrt{\frac{C_s}{C_{ns}}}\right) \tag{19}$$

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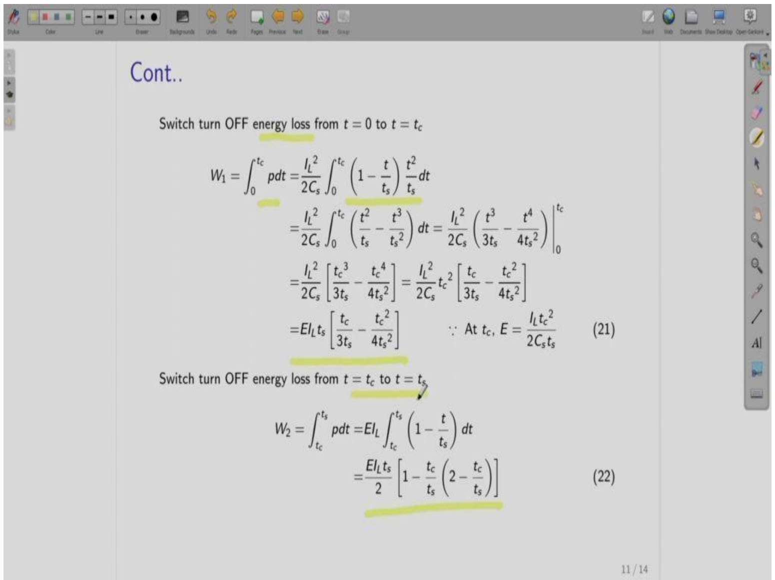

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Switch turn OFF energy loss from $t = 0$ to $t = t_c$

$$W_1 = \int_0^{t_c} pdt = \frac{I_L^2}{2C_s}\int_0^{t_c}\left(1-\frac{t}{t_s}\right)\frac{t^2}{t_s}dt$$
$$= \frac{I_L^2}{2C_s}\int_0^{t_c}\left(\frac{t^2}{t_s}-\frac{t^3}{t_s^2}\right)dt = \frac{I_L^2}{2C_s}\left(\frac{t^3}{3t_s}-\frac{t^4}{4t_s^2}\right)\Bigg|_0^{t_c}$$
$$= \frac{I_L^2}{2C_s}\left[\frac{t_c^3}{3t_s}-\frac{t_c^4}{4t_s^2}\right] = \frac{I_L^2}{2C_s}t_c^2\left[\frac{t_c}{3t_s}-\frac{t_c^2}{4t_s^2}\right]$$
$$= EI_Lt_s\left[\frac{t_c}{3t_s}-\frac{t_c^2}{4t_s^2}\right] \qquad \because \text{At } t_c,\ E = \frac{I_Lt_c^2}{2C_st_s} \tag{21}$$

Switch turn OFF energy loss from $t = t_c$ to $t = t_s$

$$W_2 = \int_{t_c}^{t_s} pdt = EI_L\int_{t_c}^{t_s}\left(1-\frac{t}{t_s}\right)dt$$
$$= \frac{EI_Lt_s}{2}\left[1-\frac{t_c}{t_s}\left(2-\frac{t_c}{t_s}\right)\right] \tag{22}$$

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So, now if we want to find out the energy loss, you integrate that power expression from time 0 to tc. This is for the switch turn OFF energy loss. Because, this time period your capacitor voltage is building up, so, the equation is different, then, from the time period tc to ts. So, we have to find out the switch loss in two parts. So, first part from 0 to tc interval, you just simply write down the power expression, and then you have to basically integrate and solve it, so, this is what finally you are going to get.

$$W_1 = EI_L t_s \left[\frac{t_c}{3t_s} - \frac{t_c^2}{4t_s^2} \right]$$

(21)

And switch turn OFF energy loss from tc to ts, so the equation is different there. So, you then you have to solve that equation, you integrate it. And if you solve it this is what you will be getting.

$$W_2 = \frac{EI_L t_s}{2} \left[1 - \frac{t_c}{t_s} \left(2 - \frac{t_c}{t_s} \right) \right]$$

(22)

So, we obtain the switch loss in two parts for the time interval 0 to tc, and tc to ts, so, to total switch loss will be the sum of these two.

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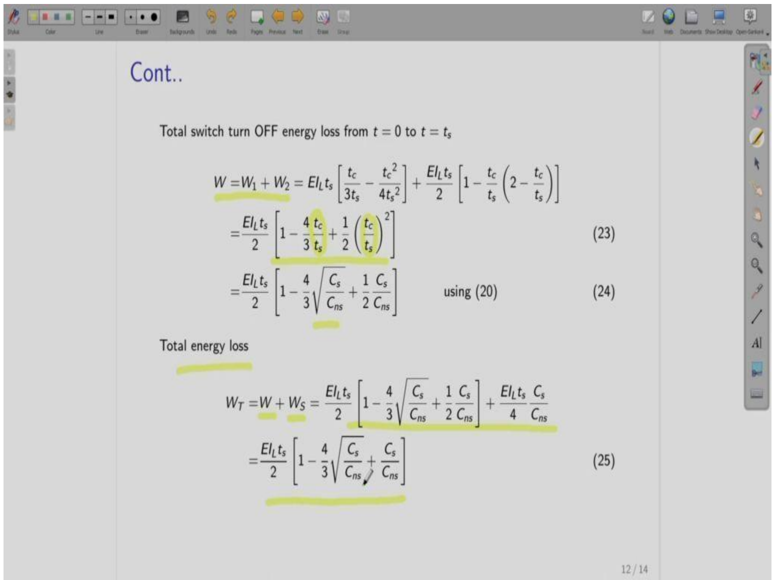

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Total switch turn OFF energy loss from $t = 0$ to $t = t_s$

$$W = W_1 + W_2 = EI_L t_s \left[\frac{t_c}{3t_s} - \frac{t_c^2}{4t_s^2} \right] + \frac{EI_L t_s}{2} \left[1 - \frac{t_c}{t_s} \left(2 - \frac{t_c}{t_s} \right) \right]$$

$$= \frac{EI_L t_s}{2} \left[1 - \frac{4}{3} \frac{t_c}{t_s} + \frac{1}{2} \left(\frac{t_c}{t_s} \right)^2 \right] \quad (23)$$

$$= \frac{EI_L t_s}{2} \left[1 - \frac{4}{3} \sqrt{\frac{C_s}{C_{ns}}} + \frac{1}{2} \frac{C_s}{C_{ns}} \right] \quad \text{using (20)} \quad (24)$$

Total energy loss

$$W_T = W + W_S = \frac{EI_L t_s}{2} \left[1 - \frac{4}{3} \sqrt{\frac{C_s}{C_{ns}}} + \frac{1}{2} \frac{C_s}{C_{ns}} \right] + \frac{EI_L t_s}{4} \frac{C_s}{C_{ns}}$$

$$= \frac{EI_L t_s}{2} \left[1 - \frac{4}{3} \sqrt{\frac{C_s}{C_{ns}}} + \frac{C_s}{C_{ns}} \right] \quad (25)$$

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So, W equal two W1 plus W2, you add these two expressions, and you solve it. So, this is what you will be getting

$$W = W_1 + W_2 = EI_L t_s \left[\frac{t_c}{3t_s} - \frac{t_c^{\,2}}{4t_s^{\,2}} \right] + \frac{EI_L t_s}{2} \left[1 - \frac{t_c}{t_s} \left(2 - \frac{t_c}{t_s} \right) \right]$$

$$W = \frac{EI_L t_s}{2} \left[1 - \frac{4}{3} \frac{t_c}{t_s} + \frac{1}{2} \left(\frac{t_c}{t_s} \right)^2 \right]$$

(25)

$$W = \frac{EI_L t_s}{2} \left[1 - \frac{4}{3} \sqrt{\frac{C_s}{C_{ns}}} + \frac{1}{2} \frac{C_s}{C_{ns}} \right]$$

(24)

Now, total energy loss will be switch loss plus snubber loss, snubber loss expression remains the same as before that what we saw in large snubber case. So, you write down both of them and you reduce it, this is what you will be getting

$$W_T = W + W_S = \frac{EI_L t_s}{2} \left[1 - \frac{4}{3} \sqrt{\frac{C_s}{C_{ns}}} + \frac{C_s}{C_{ns}} \right]$$

(25)

So, now let us see the summary of this analysis what we obtained. But before that, let us look into the minima for this total energy loss.

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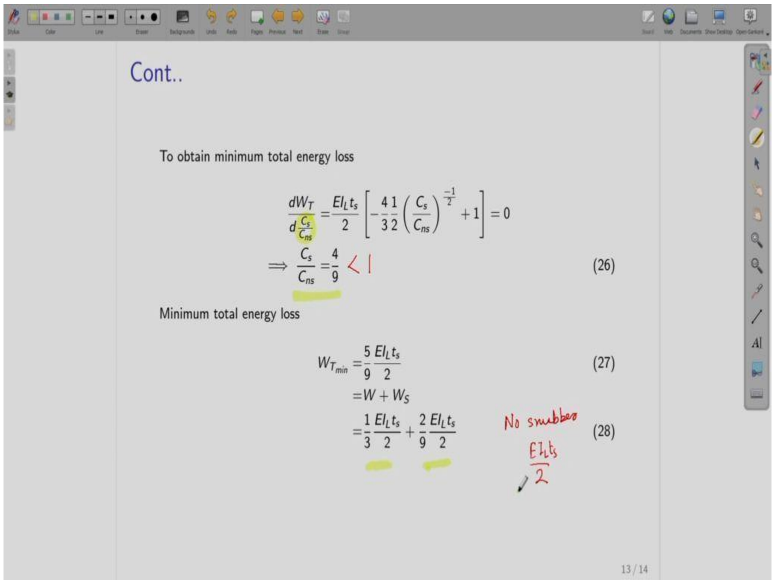

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To obtain minimum total energy loss

$$\frac{dW_T}{d\frac{C_s}{C_{ns}}} = \frac{EI_L t_s}{2}\left[-\frac{4}{3}\frac{1}{2}\left(\frac{C_s}{C_{ns}}\right)^{\frac{-1}{2}} + 1\right] = 0$$

$$\Longrightarrow \frac{C_s}{C_{ns}} = \frac{4}{9} < 1 \qquad (26)$$

Minimum total energy loss

$$W_{T_{min}} = \frac{5}{9}\frac{EI_L t_s}{2} \qquad (27)$$

$$= W + W_S$$

$$= \frac{1}{3}\frac{EI_L t_s}{2} + \frac{2}{9}\frac{EI_L t_s}{2} \qquad (28)$$

No snubber

$\frac{EI_L t_s}{2}$

So, you differentiate this total energy loss with respect to Cs by Cns. And when you differentiate that and you equate it to 0, after solving this is what you will be getting.

$$\frac{C_s}{C_{ns}} = \frac{4}{9}$$

(26)

Now, this is less than 1 and this is small snubber case analysis is also for these values to be less than 1, so, this is valid. So, minimum total energy loss will take place for this value(4/9) of snubber.

So, minimum total energy loss, then if you substitute for this Cs by Cns in this expression(25). Then, what you will be obtaining that this minimum total energy loss is

$$W_{T\min} = \frac{5}{9}\frac{EI_L t_s}{2} \qquad (27)$$

$$= W + W_s$$

$$= \frac{1}{3}\frac{EI_L t_L}{2} + \frac{2}{9}\frac{EI_L t_s}{2}$$

which is equal to W plus Ws, means your device loss plus snubber loss. And you can substitute this 4 by 9 in the expressions that you obtain for device losses as well as for snubber losses.

So, what you will be seeing is that one third of this is is the device loss, and 2 by 9 of that is the the rest of it is the snubber loss. Now, if you recall with the case of no snubber, we had obtained the power loss expression. So, for no snubber case what it was? It was equal to EIL ts by 2. So, what we observe here is that that your device losses have decreased from the case of no snubber. So, by adding snubber, we affected the turn off trajectories, means how the voltage builds up and that affects the device losses. And if we design this snubber properly, it will so happen that although there are some snubber losses, the total loss will be lesser than the case when there was no snubber. So, you reduce the stress on the device.

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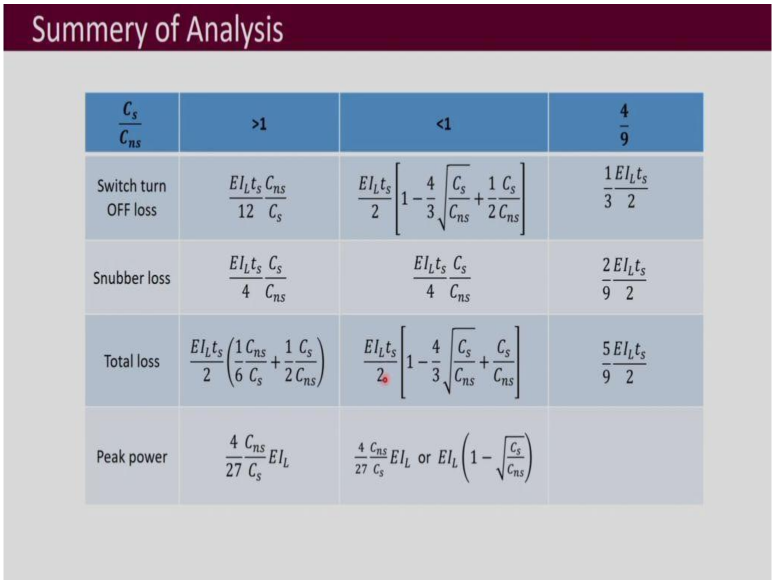
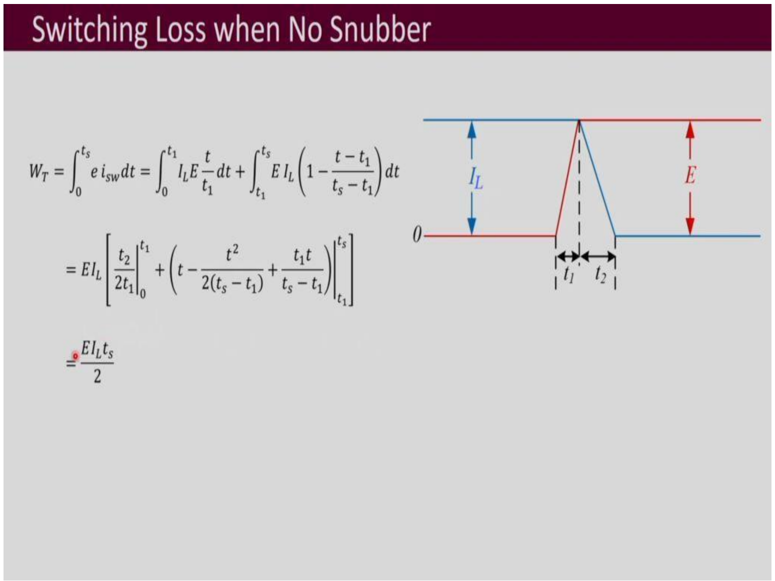


Summery of Analysis

$\frac{C_s}{C_{ns}}$	>1	<1	$\frac{4}{9}$
Switch turn OFF loss	$\frac{EI_L t_s}{12}\frac{C_{ns}}{C_s}$	$\frac{EI_L t_s}{2}\left[1-\frac{4}{3}\sqrt{\frac{C_s}{C_{ns}}}+\frac{1}{2}\frac{C_s}{C_{ns}}\right]$	$\frac{1}{3}\frac{EI_L t_s}{2}$
Snubber loss	$\frac{EI_L t_s}{4}\frac{C_s}{C_{ns}}$	$\frac{EI_L t_s}{4}\frac{C_s}{C_{ns}}$	$\frac{2}{9}\frac{EI_L t_s}{2}$
Total loss	$\frac{EI_L t_s}{2}\left(\frac{1}{6}\frac{C_{ns}}{C_s}+\frac{1}{2}\frac{C_s}{C_{ns}}\right)$	$\frac{EI_L t_s}{2}\left[1-\frac{4}{3}\sqrt{\frac{C_s}{C_{ns}}}+\frac{C_s}{C_{ns}}\right]$	$\frac{5}{9}\frac{EI_L t_s}{2}$
Peak power	$\frac{4}{27}\frac{C_{ns}}{C_s}EI_L$	$\frac{4}{27}\frac{C_{ns}}{C_s}EI_L$ or $EI_L\left(1-\sqrt{\frac{C_s}{C_{ns}}}\right)$	



Switching Loss when No Snubber

$$W_T = \int_0^{t_s} e\, i_{sw}\, dt = \int_0^{t_1} I_L E \frac{t}{t_1} dt + \int_{t_1}^{t_s} E\, I_L \left(1-\frac{t-t_1}{t_s-t_1}\right) dt$$

$$= EI_L\left[\frac{t_2}{2t_1}\bigg|_0^{t_1} + \left(t - \frac{t^2}{2(t_s-t_1)} + \frac{t_1 t}{t_s-t_1}\right)\bigg|_{t_1}^{t_s}\right]$$

$$= \frac{EI_L t_s}{2}$$

This is the summary of the analysis that we performed. So, the important equations that we obtain was is your the switch turn OFF loss, and this is for large snubber case this

$$\frac{EI_L t_s}{12}\frac{C_{ns}}{C_s}$$

is what we obtained for small snubber case,

$$\frac{EI_L t_s}{2}\left[1 - \frac{4}{3}\sqrt{\frac{C_s}{C_{ns}}} + \frac{1}{2}\frac{C_s}{C_{ns}}\right]$$

this is the expression. And then this is

$$\frac{1}{3}\frac{EI_L t_s}{2}$$

what we obtained for the minimum loss where the total loss is minimum at for that your when your Cs by Cns is equal to 4 by 9. So, for that case, we obtained this expressions(see the table in screenshot).

Further, your snubber loss that actually remains the same in these two cases,

For > 1, $\frac{EI_L t_s}{4}\frac{C_s}{C_{ns}}$ for < 1, $\frac{EI_L t_s}{4}\frac{C_s}{C_{ns}}$

it is not affected by your large snubber or small snubber. I mean the expression is not affected by that, of course your values are going to get affected. And if you substitute for that Cs by Cns, this is what you will be obtaining

$$\frac{2}{9}\frac{EI_L t_s}{2}$$

And the sum of these two, the total loss expression. So, total loss in terms of the snubber values, this

$$\frac{EI_L t_s}{2}\left(\frac{1}{6}\frac{C_{ns}}{C_s} + \frac{1}{2}\frac{C_s}{C_{ns}}\right)$$

is what you obtain for large snubber. And this one

$$\frac{EI_L t_s}{2}\left[1 - \frac{4}{3}\sqrt{\frac{C_s}{C_{ns}}} + \frac{C_s}{C_{ns}}\right]$$

is for the small snubber number, and then this is where you have the minimum total loss, this

$$\frac{5}{9}\frac{EI_L t_s}{2}$$

is the expression that you obtain. And then the peak power expressions that also we had obtained for large snubber, this

$$\frac{4}{27}\frac{C_{ns}}{C_s}EI_L$$

is the expression. For small snubber, we saw that if your the commutation time is actually greater than 2 by 3 of the turn OFF time. Then this

$$\frac{4}{27}\frac{C_{ns}}{C_s}EI_L$$

is the same as the large snubber, else it is given by this.

$$\frac{4}{27}\frac{C_{ns}}{C_s}EI_L \text{ or } EI_L\left(1-\sqrt{\frac{C_s}{C_{ns}}}\right)$$

So, these are the important expressions that we had obtained. Now, if we look into it, what we observe is that that the way these derivations are done, all the expressions are in terms of this snubber size, snubber size with respect to your normal snubber. So, Cs by Cns is the ratio in which all the expressions are obtained. And there are other terms which are your EIL ts by 2, this is also a factor. You can call it as like as a multiplication factor, which is also present in almost all the cases. So, now, if we see, previously we had obtained this switching loss when no snubber is present, that is in terms of this EIL ts by 2.

So, if we normalize this expression with respect to the case when there is no snubber. So, your EIL ts by 2 will disappear, so, it will be a normalized loss expressions that you will be obtaining. And so, those will be just in terms of some ratios, and then the whole thing can be like a generalized expression, which you can use it for any design of your converter, irrespective of your values of EIL ts. So, that is what then is done. And these are then plotted as normalized with respect to the case when there is no snubber.

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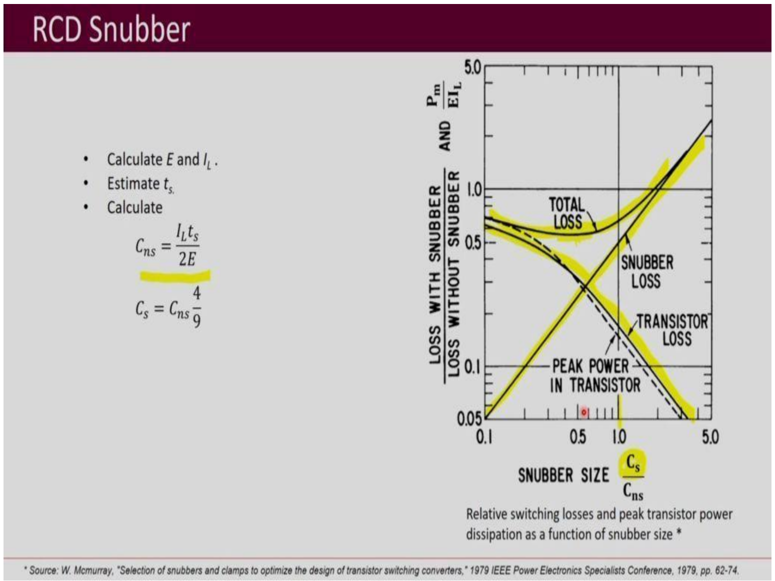


RCD Snubber

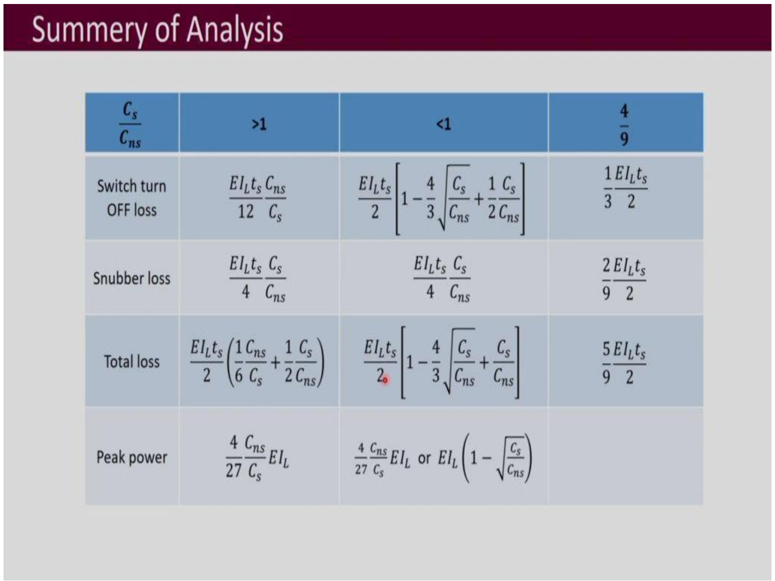
- Calculate E and I_L.
- Estimate t_s.
- Calculate

$$C_{ns} = \frac{I_L t_s}{2E}$$

$$C_s = C_{ns}\frac{4}{9}$$

Relative switching losses and peak transistor power dissipation as a function of snubber size *

* Source: W. Mcmurray, "Selection of snubbers and clamps to optimize the design of transistor switching converters," 1979 IEEE Power Electronics Specialists Conference, 1979, pp. 62-74.



Summery of Analysis

$\frac{C_s}{C_{ns}}$	>1	<1	$\frac{4}{9}$
Switch turn OFF loss	$\frac{EI_L t_s}{12}\frac{C_{ns}}{C_s}$	$\frac{EI_L t_s}{2}\left[1-\frac{4}{3}\sqrt{\frac{C_s}{C_{ns}}}+\frac{1}{2}\frac{C_s}{C_{ns}}\right]$	$\frac{1}{3}\frac{EI_L t_s}{2}$
Snubber loss	$\frac{EI_L t_s}{4}\frac{C_s}{C_{ns}}$	$\frac{EI_L t_s}{4}\frac{C_s}{C_{ns}}$	$\frac{2}{9}\frac{EI_L t_s}{2}$
Total loss	$\frac{EI_L t_s}{2}\left(\frac{1}{6}\frac{C_{ns}}{C_s}+\frac{1}{2}\frac{C_s}{C_{ns}}\right)$	$\frac{EI_L t_s}{2}\left[1-\frac{4}{3}\sqrt{\frac{C_s}{C_{ns}}}+\frac{C_s}{C_{ns}}\right]$	$\frac{5}{9}\frac{EI_L t_s}{2}$
Peak power	$\frac{4}{27}\frac{C_{ns}}{C_s}EI_L$	$\frac{4}{27}\frac{C_{ns}}{C_s}EI_L$ or $EI_L\left(1-\sqrt{\frac{C_s}{C_{ns}}}\right)$	

So, this with respect to this snubber size that means this ratio Cs by Cns, and the plot of loss of width snubber by loss without snubber. So, basically it is a normalized thing, you get rid of that EIL ts by 2 term. And also, this power is also plotted, your peak power expression and that is divided by EIL. Because you can see here if you want to normalize this peak power, you have to divide it by EIL, because that is the term which actually is specific to the converter. And this ratio is not specific to any converter when we are doing this analysis. So, then if you, when you plot it, this one is the snubber loss plot.

You can see it is continuously increasing with your snubber size see Cs by Cns. Then this one is your transistor loss, so, that is decreasing with the size of the snubber. And this is in the total loss, the snubber loss plus the device loss. So, what we see is that this minimum occurs before one and somewhere around here it is occurring, so, that is your 4 by 9 what we had obtained is the total loss where it becomes minimum. So, and around this value actually the minima, you can see that it is relatively insensitive, it is not varying too much. So, around this value you can actually play around, you adjust the values a little bit, it does not change the total loss much.

And one more thing that you observe here is that that as you increase this Cs value, as you keep on increasing your device loss, your transistor loss is decreasing. So, you are reducing the device's stress, your device losses are increasing. But, the cost then you pay is that you use to store energy is increasing and that is what will become the snubber loss, so that is going to increase. So that is what you can observe here. And so, we would like to reduce device stress, we would like to minimize the losses, and then that becomes the optimum snubber design your RCDs snubbers. So, those values of your Cs is what we are supposed to choose.

So, how can we do the snubber design? So, you calculate your E and IL for your converter, which we are designing, this something you will be knowing when you design the converter and you estimate your ts that is your turn OFF time. Now, this is something you have to estimate, turn OFF time is not fixed. We did the assumption that in all these cases, your large snubber, small snubber, normal snubber ts is fixed. It is not getting affected by the choice of this snubber value, but in reality, it does get affected. It gets affected by many things. It gets affected by what kinds of parasitics are present in your converter, how good your layout is, your device, so many things, your turn OFF time and turn on time they get affected.

So, you try to have an estimate of your ts, which is definitely you can estimate, you can start with the datasheet values also, you can do some preliminary experiments to observe the ts value. So, estimate your ts and then you have this expression for obtaining the normal snubber capacitance IL ts by 2E. And then from there you can start for your starting design, you can choose this number value Cs as Cns 4 by 9. That is what you can choose the value of capacitance to start your design with. And then further as I said, you can fine tune with the experimental results. And how do you choose your Rs value?

So, this whole of Cs energy that gets dissipated in Rs, you can use that expression also to obtain your value for Rs. And one more thing that you can observe here this peak power Pm, this normalized peak power Pm with respect to EIL is also plotted here, and this is that dotted line that that is shown here. Now, this is also something you should pay attention to, because when we do the snubber design, we would like to keep the device within the SOA limits. So, you can observe that with respect to your snubber size, what is the peak power that is expected, and if it is well within the SOA the safe operating area or not?

And if it is not, then you can adjust the snubber value, so that it goes within your SOA limits. So, you may not always design it for the minimum total loss as you might have to modify it also. And finally, the values as I said gets adjusted and modified based on your experimental results, what waveforms do you observe. So, this is the way you can do your RCD snubber design.

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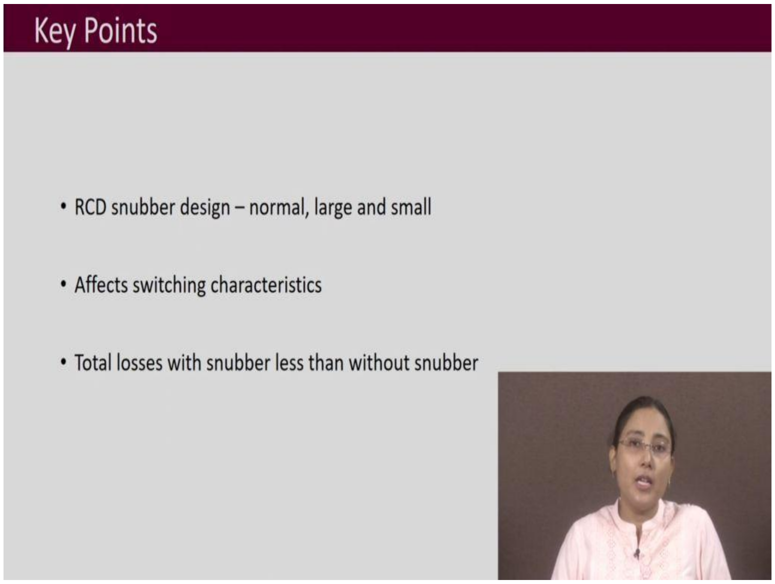

Key Points

- RCD snubber design – normal, large and small
- Affects switching characteristics
- Total losses with snubber less than without snubber

So, the key points of this lecture are that your RCD snubber design analysis is done by dividing into three parts: normal snubber, small snubber, and large snubber. And what we saw is that choice of snubber affects your switching characteristics, and we can reduce the device stress by properly choosing the values of these snubbers. And we can also try to keep it within the SOA limits by proper choice of your snubber design.

And also, what we observed is that that your device losses are getting affected in, and it can be lesser than what it is when there is no snubber. So, your total loss of your converter basically the switching loss need not increase, because you are adding a snubber resistance. It may reduce also if you have chosen proper values of snubbers. Thank you.