Application Note
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Turn-Off Snubber Design for High Frequency Modules

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Turn-off snubbers are passive circuits made of diodes, resistors and capacitors dedicated to storing energy for a short period to:

- Decrease switch power losses during turn-off
- Modify switching I-V diagram to fit safely within the switching safe operating area

1- Hard-Switched Inductive Load Turn-Off

Assuming that the $\frac{L}{r}$ load time constant is much longer than the switching time, current in the load can be considered constant during turn-off. The sum of currents in the diode and in the transistor remains constant. Forward voltage of the freewheeling diode being negligible, all supply voltage is applied to the transistor during turn-off. (See fig. 1.)

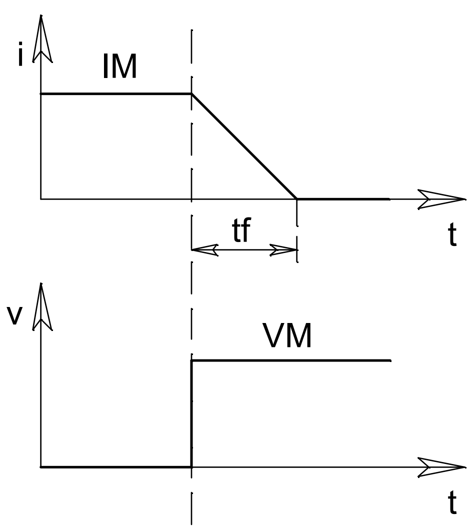

Fig.1 Switch turn-off behaviour with an inductive load

Energy in the transistor is given by the relationship:

$$E_{off} = \int_0^{tf} V \cdot i \cdot dt = \frac{V_M \cdot I_M \cdot t_f}{2}$$

In practice, the voltage is ramping up with a time equal to trv. Hard-switched turn-off switching energy is the area of the product of switch voltage and current. Since the overlap in voltage and current is shaped, like a triangle, the area is one half the base (trv + tf) times height (bus voltage times load current). (See fig.2).

$$E_{off} = \int_0^{t_{rv}+t_f} v_M \cdot i_M \cdot dt = \frac{V_M \cdot I_M \cdot (t_{rv} + t_f)}{2}$$

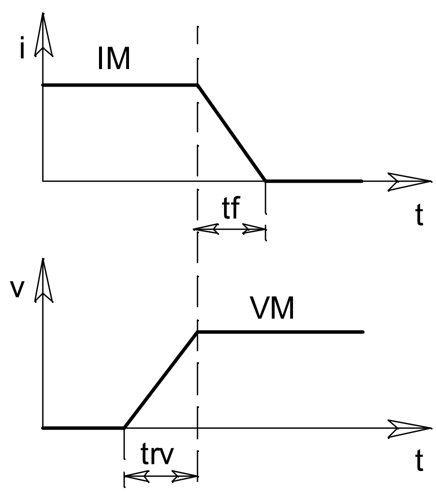

Fig.2 Experimental turnoff behaviour with an inductive load

2- Turn-Off Snubber Theory of Operation

Fig. 3 describes the electrical diagram of a turn-off snubber. Capacitor C is the key element of the circuit. The diode and resistor are only used to prevent instantaneous discharge of the energy stored in the capacitor while the switch turns on.

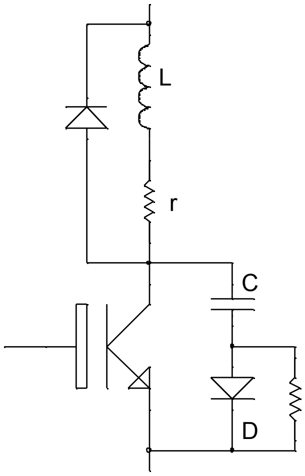

Fig.3 Chopper with turn-off snubber circuit

As a first step in analyzing the operation of the snubber, we treat the current in the load during turn–off as constant. The turn-off sequence with the snubber is shown in Figure 4.

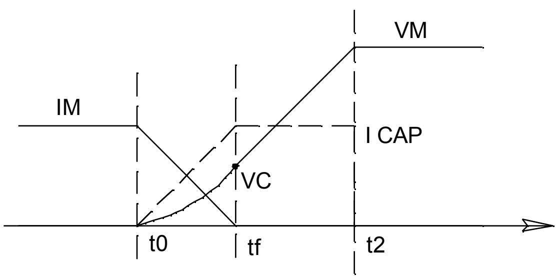

Fig.4 Turn off behaviour with snubber circuit connected across the switch.

During the time interval t_0 to t_f, current in the switch decreases while current in the capacitor increases such that the sum of the currents is constant.

For simplicity, let us set the time at t_0 equal to zero. At the end of the turn-off time t_f, the voltage across the capacitor is calculated as the area of a triangle, given by the relationship:

$$V_{Ctf} = \frac{1}{C}\int_{t_0=0}^{t_f} i_C \cdot dt \Rightarrow V_{Ctf} = \frac{I_M \cdot t_f}{2 \cdot C} \qquad (1)$$

At the end of the interval t_f to t_2, the capacitor C is charged up to the voltage V_M. It is only during the last phase ($t > t_2$) that current switches from C to the freewheeling diode.

During turn-off, snubber diode D conducts, and the voltage across the capacitor equals the voltage across the switch (ignoring the small voltage drop across the snubber diode). During the interval t_0 to t_f the capacitor current is

$$i_C = \frac{I_M \cdot t}{t_f - t_0} = \frac{I_M \cdot t}{t_f}.$$

The capacitor and switch voltage is

$$v_C = \frac{1}{C}\int \frac{I_M}{t_f} \cdot t \cdot dt + V_{Czero} = \frac{I_M \cdot t^2}{2 \cdot C \cdot t_f} + V_{Czero}$$

where V_{Czero} is a constant of integration that is solved for by evaluating at $t = t_f$.

$$v_C\big|_{t=t_f} = \frac{I_M \cdot t_f^{\,2}}{2 \cdot C \cdot t_f} + V_{Czero} = \frac{I_M \cdot t_f}{2 \cdot C} + V_{Czero} = V_{Ctf}$$

Since $V_{Ctf} = \frac{I_M \cdot t_f}{2 \cdot C}$, V_{Czero} must be zero. Substituting V_{Ctf} into the equation for v_C, we get

$$v_C = \frac{I_M \cdot t_f}{2 \cdot C} \cdot \frac{t^2}{t_f^2} = V_{Ctf}\left(\frac{t}{t_f}\right)^2$$

Current in the switch is given by the relationship

$$i_{sw} = I_M\left(1 - \frac{t}{t_f}\right) \qquad (2)$$

Therefore the energy dissipated in the transistor during turn-off, derived from (1) and (2), is given by:

$$E_{off} = \int_0^{t_f} i_{sw} \cdot v_C \cdot dt = V_{Ctf} \cdot I_M \int_0^{t_f}\left(1 - \frac{t}{t_f}\right)\cdot\left(\frac{t}{t_f}\right)^2 \cdot dt$$

$$= \int_0^{tf}\left(\frac{I_M^{\,2} \cdot t_f}{2 \cdot C}\right)\cdot\left(1 - \frac{t}{t_f}\right)\cdot\left(\frac{t}{t_f}\right)^2 .dt$$

$$= \frac{1}{12} \cdot \frac{I_M^{\,2} \cdot t_f^{\,2}}{2 \cdot C}$$

Notice that the larger the snubber capacitance, the lower E_{off} is. Also note that E_{off} with a turn-off snubber does not depend on the bus voltage as in the hard-switched case. E_{off} depends on the transistor current and the current fall time with or without a turn-off snubber.

The role of the turn-off snubber is essentially to limit the voltage rise across the switch while the current through the switch falls to zero. The reduction in switching voltage significantly reduces turn-off loss in the switch and therefore improves reliability.

The E_{off} calculation above is based upon an ideal case of linearly decreasing switch current during turn-off. Turn-off may exhibit a tail current behaviour with some IGBT types. In this case the theoretical E_{off} calculation may appear a little pessimistic but gives a good idea of efficiency improvement that needs in any case to be validated by testing the actual circuit.

The turn-off snubber is not very effective at limiting over-voltage transients. If it is necessary to limit over-voltage, the following circuit can be added.

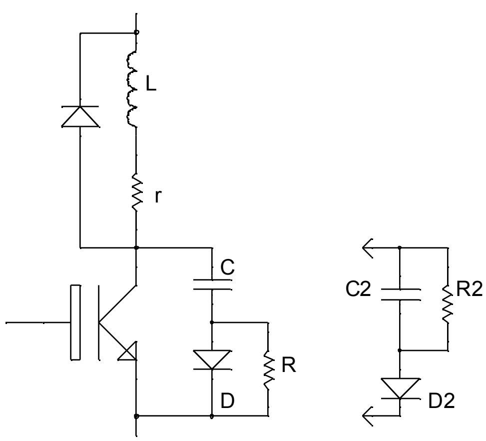

Fig.5 Chopper with turn-off snubber and over voltage protection circuit.

The role of R2, D2, and C2 is very different from the one of a turn-off snubber.

In this case capacitor C2 is charged to maximum voltage V_M, and diode D2 conducts only during over-voltage spikes. The R2, D2, C2 network acts as a tranzorb.

3- Determining Snubber Component Values and Ratings

3-1 Capacitor C

As shown above, capacitor C has a direct impact on turn-off energy and losses:

$$E_{off} = \frac{1}{12} \cdot \frac{I_M^{\,2} \cdot t_f^{\,2}}{2 \cdot C}$$

$$P_{off} = \frac{1}{12} \cdot \frac{I_M^{\,2} \cdot t_f^{\,2}}{2 \cdot C} \cdot f$$

Usually film capacitors are used, such as polypropylene or similar type.

Following requirements must be met by the capacitor ratings:

- **Maximum $\frac{d_v}{d_t}$ value.**

In practice, the capacitor is chosen such that its maximum $\frac{d_v}{d_t}$ rating is :

$\frac{d_v}{d_t} > \frac{I\,peak}{C}$, **where** Ipeak is the maximum peak current in the capacitor.

- **Voltage rating**

Voltage rating of the capacitor must be higher than the DC supply voltage V_M.

- **RMS current rating.**

For high frequency operation, reactive power in the capacitor may become important and care must be taken to not exceed the maximum RMS current rating of the capacitor. As a general rule:

$$I_{Crms} = \sqrt{\frac{1}{T_{sw}}\left(I_{1pk}^2 \cdot t_1 + I_{2pk}^2 \cdot t_2\right)} = \sqrt{f_{sw}\left(I_{1pk}^2 \cdot t_1 + I_{2pk}^2 \cdot t_2\right)}$$

Where f is the switching frequency,
I_{1PK} is the peak current at turn-off,
t_1 is the current pulse duration at turn-off,
I_{2PK} is the peak current at turn-on, and
t_2 is the current pulse duration at turn-on.

3-2 Resistor R

The energy stored in the capacitor is given by the relationship

$$E_C = \frac{C \cdot V_M{}^2}{2}$$

When the switch turns on, the energy stored in the capacitor is dissipated in the resistor R.

$$P_R = \frac{C \cdot V_M{}^2}{2} \cdot f$$

Several criteria other than its power dissipation dictate the selection of resistor R:

- The discharge current at turn-on must not exceed the maximum pulse current I_{CM} of the switch. In practice, the value for R can be chosen according to the following rule:

$$R > \frac{V_M}{I_{CM} - I_M - I_{RM}}$$, where I_{RM} is the snubber diode recovery current.

- The capacitor C must be completely discharged at the end of switch turn-on (t_r), otherwise there is a risk of exceeding the transistor safe operating area limits.

3-3 Diode D

The snubber diode voltage rating must be higher than the supply voltage value. Usually it has the same voltage rating as the main switches. It conducts current only during capacitor charging. Therefore a diode with lower current capability than the load current can be chosen, but the diode must be able to handle a peak current equal to the load current. The snubber diode must be a fast recovery type. At high frequency operation, care must be taken to appropriately cool the diode.

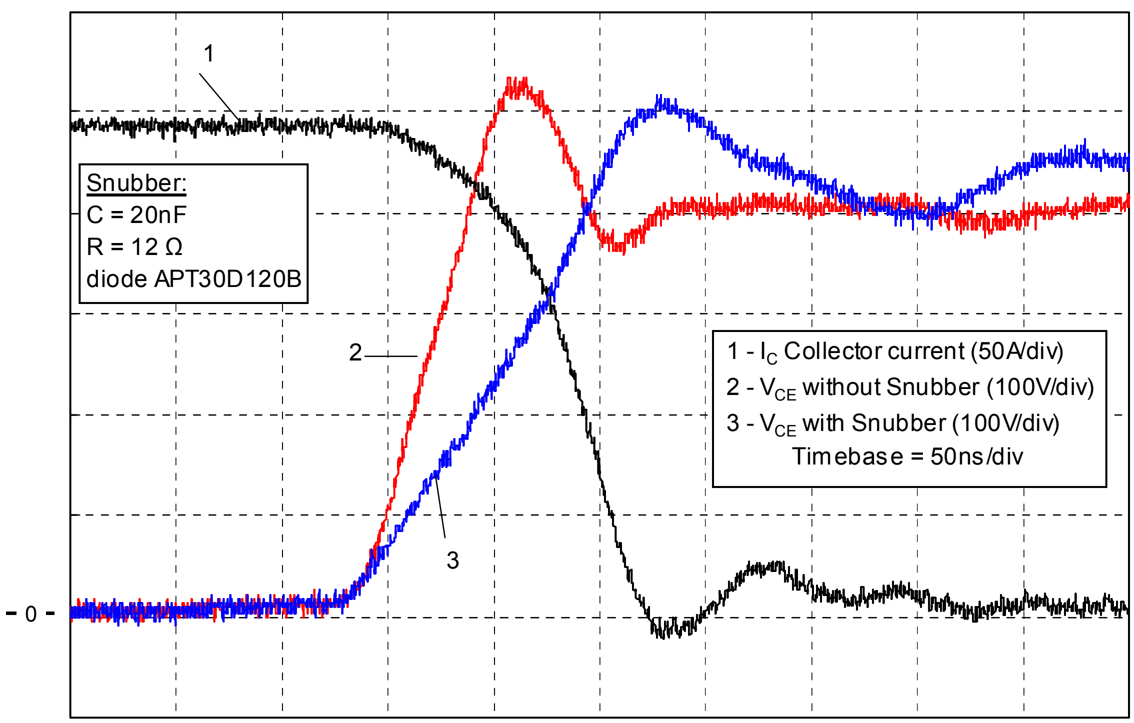

Fig.6 Influence of 20nF snubber capacitor on turn off behaviour of an APTGF300A120 module

4- Specific case of soft switching techniques

To operate at high frequency, it is wiser to adopt soft switching techniques like Zero Voltage Switching (ZVS) that simply eliminate turn-on losses. Given that the switch turns on at zero voltage, it is not necessary in this case to limit the snubber capacitor discharge current, and both diode D and resistor R are no longer needed.

Bibliography:

Les circuits d'aide a la commutation / Le transistor de puissance dans son environnement – Jean Marie Peter