A STUDY OF THE EFFECTS OF SNUBBER ON SWITCHING LOSS AND EMI IN AN MCT CONVERTER

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Abstract - The paper presents a nonlinear analysis of the standard snubber used to protect an MCT in a dc chopper circuit. Expressions for the voltage and current during switching as well as the base values for the snubber capacitor and inductor, are derived. These results are used to determine the optimum values for the snubber elements that result in minimum switching loss. The effect of the snubber in reducing the peak power loss in the MCT is illustrated by recording the voltage, current, and power during switching. The paper also studies the effect of the standard snubber in reducing the electromagnetic interference (EMI). The study is supported by obtaining the plots of the radiated electric and magnetic emissions from the MCT chopper.

1. Introduction

The MOS Controlled Thyristor (MCT) has a number of advantages as compared to other power semiconductor devices. It has a low conduction drop and is capable of operating at frequencies as high as 100 kHz. Like other devices, the MCT is to be protected against transient voltage and current spikes by using a suitable snubber. An R-C snubber modifies the voltage and current transients during switching, and limits the voltage spike and the rate of voltage rise [1], [2]. Snubbers are capable of protecting the MCT by modifying the switching trajectory so that the trajectory lies well within the safe operating area (SOA) during turn-on and turn-off. When the MCT operates at high frequencies, the switching loss increases due to the finite time taken for the voltage and current to decay or build up. A careful choice of the snubber values becomes necessary to reduce the switching losses. The operation of an R-C-D snubber has been analyzed by linearizing the voltage and current variations during switching [3].

As the switching speed increases, the voltages and currents controlled by the MCT will be increasingly charged with harmonic components of the switching frequency. This will result in electromagnetic interference (EMI), disrupting the performance of other equipment as well as its own proper operation. The most effective way of dealing with the EMI is to prevent the EMI from being generated at the source. This approach significantly reduces the potential of radiated and conducted interference, thus reducing the need for filters, shields, and other protective measures. A properly designed snubber reduces both the *dv/dt* (turn-off snubber) and the *di/dt* (turn-on snubber) and hence is effective in reducing EMI.

The paper presents a nonlinear analysis of the operation of the standard snubber R-C-D used in an MCT chopper circuit. The expressions for the voltage and current during switching and the base values for the snubber capacitor and inductor are derived. The results are used to determine the optimum values for the snubber elements that result in minimum switching loss. The final choice of the element values is made by experimentally measuring the switching loss. The waveforms that illustrate the modification in the switching characteristics, resulting in the minimization of the voltage-current product, are shown. The effect of the snubber in reducing the EMI is studied by first measuring the radiated emissions without the snubber and then with the optimum snubber values. The plots of the radiated electric and magnetic fields are used to demonstrate the effectiveness of the snubber in reducing the EMI potential.

2. Snubber Configuration

The power circuit of an MCT chopper including the snubber circuit, is shown in Fig. 1. The circuit consists of a turn-off snubber with R_s, C_s, and D_s, and a turn-on snubber with L_s and D_{Ls}. The turn-off snubber helps to reduce the peak power and the total power dissipated in the MCT by reducing the voltage across the MCT when the anode current decays to zero. During turn-off, the difference between the load current i_L and the anode current i_A flows through the capacitor C_s. The rate at which the anode voltage v_{AK} rises, depends on the capacitor current which in turn is inversely proportional to the value of C_s.

The series-connected turn-on snubber is used to reduce the rate of change of the anode current di_A/dt. When the device turns on, the difference

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between the supply voltage and the anode voltage appears across the inductor L_s. This difference in voltage determines the rate at which the anode current i_A rises. A fast recovery diode is used to realize D_{Ls} so that the MCT can withstand the switching transients when it turns off.

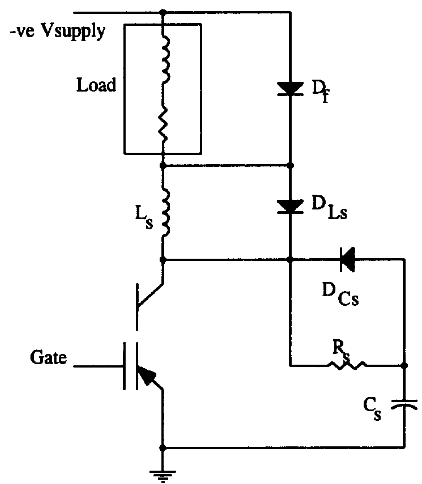


Fig. 1: Snubber circuit for an MCT.

3. Analysis of Snubber Performance

The performance of the snubber of Fig. 1 has been analyzed assuming linear variations for the voltage (current) during turn-off (turn-on) [3]. The analysis is valid for most of the power electronic devices like BJT, SCR, and GTO. In the present analysis, the voltage and current variations are assumed to be nonlinear, making the analytical waveforms closely approximate the experimental waveforms. In the analysis, the supply voltage and load current are assumed to be constant during switching. The performance of the turn-on snubber and the turn-off snubber are treated separately.

a) Turn-on transient

At the instant of turn-on, the voltage across the inductor L_s can be expressed as:

$$v_{Ls}(t) = V_s - v_{AK}(t) = L_s \frac{di_A}{dt}. \quad (1)$$

The actual variation of the anode-to-cathode voltage $v_{AK}(t)$ will be exponential in nature. In the present analysis, it is assumed as:

$$v_{AK}(t) = \frac{mV_s}{t+m} \quad (2)$$

where m is a constant determined from the voltage response. At $t = t_{fv}$, the fall time of the device voltage, the anode voltage falls to 10% of V_s. Thus, $v_{AK}(t)$ can be expressed as:

$$v_{AK}(t) = V_s \frac{t_{fv}/9}{t + t_{fv}/9}. \quad (3)$$

Substituting equation (3) into (1) and integrating, the current through the MCT is given by:

$$i_A(t) = \frac{V_s}{L_s}\left(t - \frac{t_{fv}}{9}\ln\left(1 + \frac{9t}{t_{fv}}\right)\right). \quad (4)$$

The charging time is dependent on the size of the snubber capacitor or inductor. The base value of the inductor is the one for which the snubber operation occurs exactly during the complete fall time [3]. The base value of the snubber inductor L_{sb} is obtained by setting $i_A(t_{fv}) = I_L$ where I_L is the steady state value of load current. The value of L_{sb} is given by:

$$L_{sb} = 0.744 \frac{V_s t_{fv}}{I_L}. \quad (5)$$

The base inductor value is used as a normalizing quantity. The device response and the switching loss depend on how large the snubber components are with respect to the base value.

b) Turn-off transient

The analysis of the turn-off transient can be done using duality on the turn-on transient. During turn-off, the capacitor current i_{cs} can be expressed as:

$$i_{cs} = I_L - i_A(t) = C\frac{dv_{AK}}{dt}. \quad (6)$$

During turn-off, the anode current can be obtained as:

$$i_A(t) = I_L \frac{t_{fi}/9}{t + t_{fi}/9} \quad (7)$$

where t_{fi} is the fall time for the device current. Combining equations (6) and (7), the device voltage during turn-off can be expressed as:

$$v_{AK}(t)=\frac{I_L}{C_s}\left(t-\frac{t_{fi}}{9}\left(1+\frac{9t}{t_{fi}}\right)\right). \quad (8)$$

The base value of snubber capacitor is obtained by setting $v_{AK}(t_{fi}) = V_s$. It is given by:

$$C_{sb} = 0.744\frac{I_L t_{fi}}{V_s}. \quad (9)$$

4. Switching Losses

The losses in the MCT chopper of Fig. 1 occurs in the resistor R_s and in the device. The switching loss is due to the transient variations of the voltage and current during turn-on and turn-off and it increases with the switching frequency. The switching loss in the device was computed by recording the waveforms of the voltage (v_{AK}) and current (i_A) associated with the device and integrating the product $v_{AK}i_A$. The power dissipated by the resistor R_s was computed in a similar way. Fig. 2 shows the power dissipated by the MCT and the resistor R_s for different values of C_s. Normalized values are used for both the capacitance and power loss.

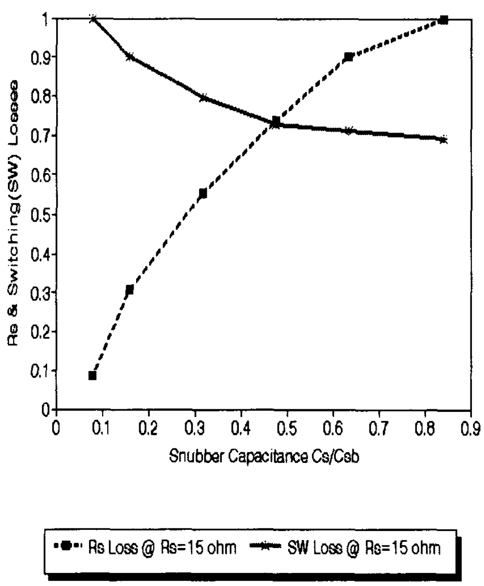


Fig. 2: Switching and snubber losses at different capacitor values.

In order to have a low value of switching loss in the device, large values of snubber capacitor and inductor are needed. However, the power loss in R_s increases as the values of the snubber capacitor and inductor are increased. The value of R_s should be large enough to prevent the discharge current from exceeding the MCT current rating but small enough to ensure that the capacitor is fully discharged during the minimum on-state period of the MCT. The range of the snubber resistance is given by:

$$R_{smin} = 10\frac{V_s}{I_L} \quad (10)$$

$$R_{smax} = \frac{t_{\text{on-state, min}}}{4C_s} \quad (11)$$

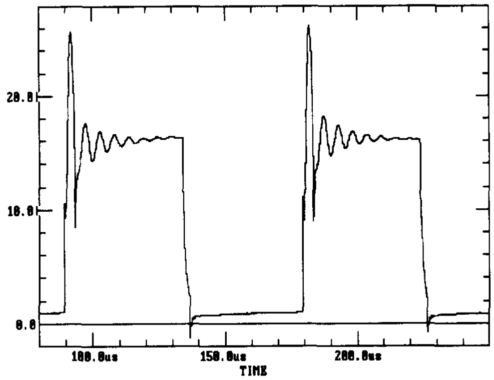
5. Waveforms and Switching Trajectory

The switching waveforms of the MCT chopper were obtained using a digital storage oscilloscope. The effectiveness of the snubber in suppressing the transient spikes in the voltage and current waveforms was studied by obtaining the voltage and current waveforms for two different values of snubber capacitor. One of the capacitor voltages is the optimum one obtained for minimum switching loss. The second one is a capacitor with a low value (non-optimum). Fig. 3 shows the waveforms of anode-to-cathode voltage and the anode current, and the switching locus with a non-optimum snubber capacitor. It can be seen that there is a large overshoot in both the voltage and current waveforms. There are also prolonged oscillations in the voltage waveform. The switching locus exhibits overshoots which result in operation outside the SOA. Fig. 4 shows the waveforms with an optimized snubber-capacitor value. The waveforms have smaller overshoot and the transitions are mostly within the SOA.

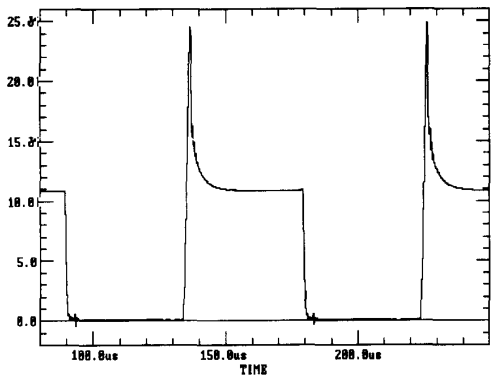
Fig. 5 shows the waveforms of the instantaneous power dissipated by the MCT for a non-optimum and an optimum snubber. With a non-optimum snubber capacitor, the voltage and current variations overlap and this results in a large peak for the instantaneous power. The average power loss is also high. With an optimum snubber, the voltage and current variations are displaced from each other. The current is forced to be small when the voltage undergoes a variation and vice versa. With the result, the peak value of power and the average loss are comparatively small.

6. Effect of Snubber on EMI

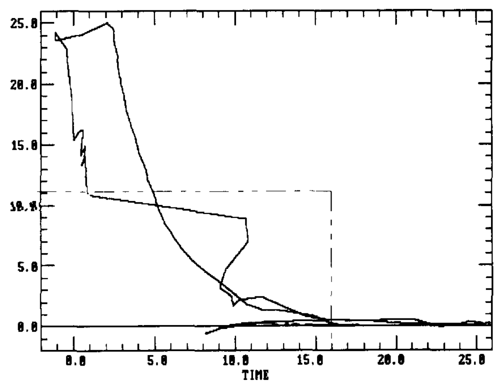
The effect of the snubber in suppressing the EMI was studied by measuring the emissions with and without a snubber [3], [4]. All the cables were connected and configured in such a way that the



(i) Anode-to-cathode voltage v_{AK}.

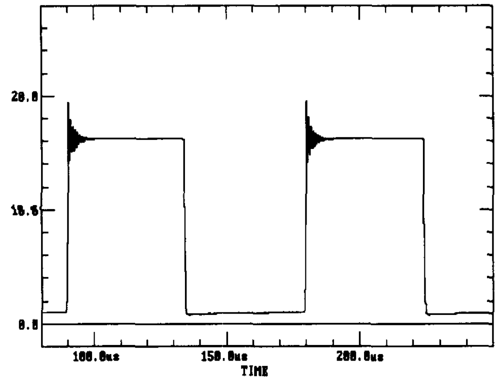


(ii) Anode current i_A.

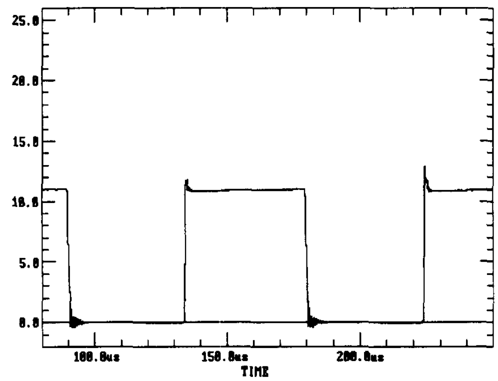


(iii) Switching locus.

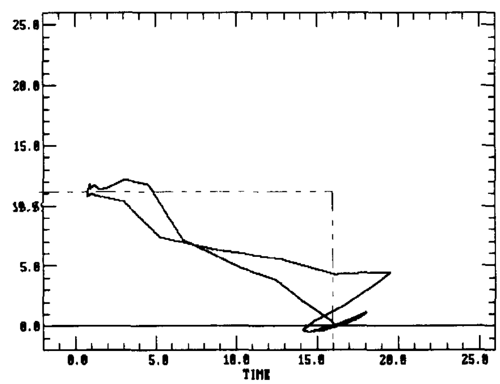
Fig. 3: Waveforms and switching locus for a non-optimized snubber.



(i) Anode-to-cathode voltage v_{AK}.



(ii) Anode current i_A.



(iii) Switching locus.

Fig. 4: Waveforms and switching locus for an optimized snubber.

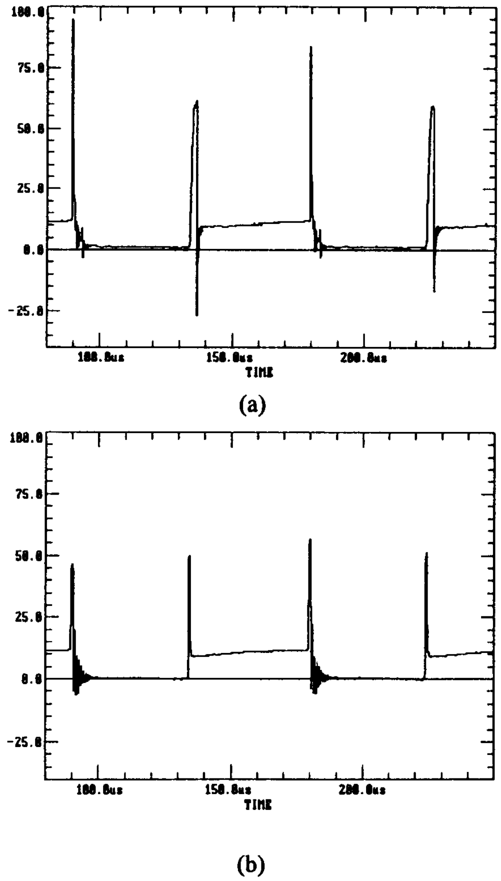


Fig. 5: Instantaneous power dissipation with (a) non-optimized and (b) optimized snubber.

emissions are maximum. The radiated electric and magnetic emissions were measured using a tuned dipole-antenna and a loop antenna, respectively. The antennas were kept at a distance of 1 m away from the device-under-test. The measurements were made with the dipole antenna in the horizontal position and the loop antenna in the vertical position. A 20 m long double-shielded cable was used to connect the antenna to the spectrum analyzer (Tektronix 2712). In addition, two short cables were used to connect the spectrum analyzer and an external attenuator. The cable loss (CL) was measured using a microwave synthesizer. The radiated emissions were then recorded by a spectrum analyzer which uses a peak detector to record the maximum signal level at the desired frequency. The peak values of the radiated electric and magnetic field intensities at all harmonics of the fundamental frequency were recorded. The spectrum analyzer has an input impedance of 50 Ω.

The equation used to calculate the electric field intensities for different frequency ranges is given by [4]:

$$E(\mathrm{dB}\mu\mathrm{V/m}) = P(\mathrm{dBmW}) + 10\log(50) + AF(\mathrm{dB}) + CL(\mathrm{dB}) \qquad (12)$$

where P is the reading of the spectrum analyzer and AF is the antenna factor. The cable loss CL remains fairly constant over the entire frequency range at 0.2 dB. The plots of the radiated electric and magnetic fields without a snubber are shown in Fig. 6. The corresponding plots with an optimum snubber are shown in Fig. 7.

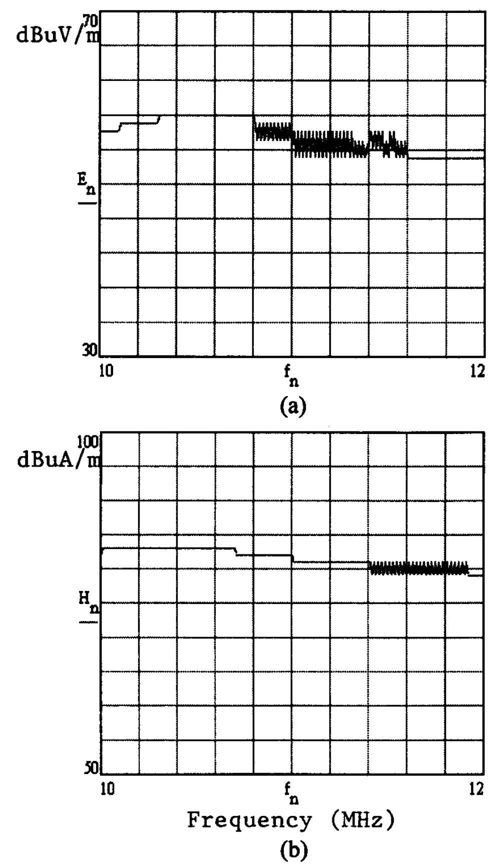


Fig. 6: Plots of the radiated (a) electric and (b) magnetic emissions without snubber.

The plots show the fields in the selected range of 10 to 12 MHz just to illustrate the effect of the snubber in attenuating the switching harmonics. Similar observations were made in other ranges as

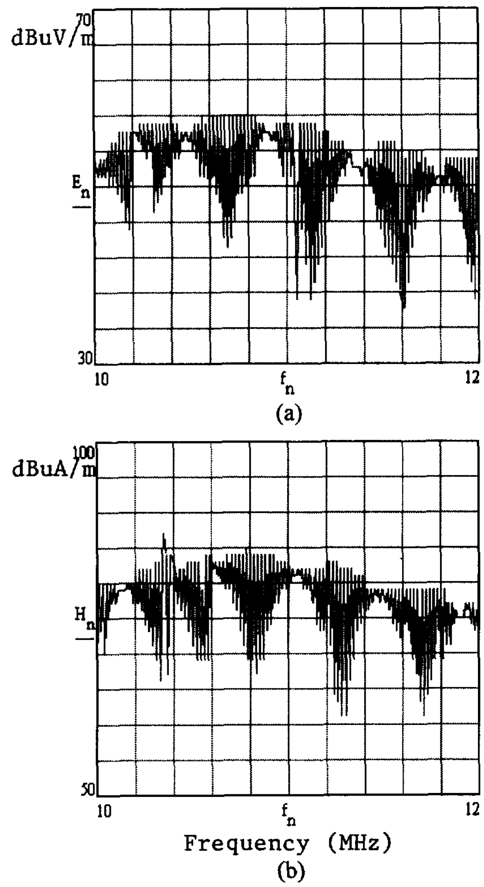


Fig. 7: Plots of the radiated (a) electric and (b) magnetic emissions with snubber.

well. Figs. 6 and 7 show that the envelopes are almost identical with and without a snubber. The plots of Fig. 6 show the presence of all the harmonics with a relatively constant amplitude when there is no snubber. However, with the addition of a proper snubber, several of the intermediate frequencies are attenuated by as much as 5 to 20 dBμV/m. Therefore, it is evident that a snubber can be used to reduce the EMI potential of power converters.

7. Conclusions

The paper presents a nonlinear analysis of the performance of an R-C-D snubber used to protect an MCT. Expressions for the base values of the snubber capacitor and inductor are derived. The effect of the snubber capacitor on the switching loss is studied. Experimental waveforms of the MCT chopper and switching loci, for two different cases are shown. The paper also studies the effect of a snubber in reducing the EMI caused by the switching action in the chopper. Plots of the electric and magnetic fields with and without chopper are used to prove the result.

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