# RC Snubber Circuit Design for Thyristor using Turn-Off Model in Pspice

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**Abstract:** ***In this paper, we present a typical RC snubber circuit design procedure for a phase controlled thyristor by considering reverse recovery process. In the snubber circuit design of high power electronic circuits, the reverse recovery process of the thyristor must be taken into consideration in order to calculate maximum device stress, maximum reverse $\frac{dv}{dt}$, maximum reverse $\frac{di}{dt}$ reverse energy loss of the power device and total turn-off of the device. In this paper, thyristor turn-off model is used to analyze the transient behavior of the thyristor during reverse recovery process. Utilizing the Pspice result analysis, a systematic RC snubber circuit design approach is described for a given thyristor.***

**Keywords:** Snubber Circuit, Turn-off Model, Reverse Recovery Process, Reverse Overvoltage Peak, Anode Current

## 1. Introduction

**S**emiconductor devices are known to be very powerful in controlling high currents and voltages. In spite of that, they are very susceptible to violations of the safe-operating conditions which may lead to their failure. When a phase control device has to turn off its current under inductive load conditions, it is very important that the voltage between anode and cathode remains inside the acceptable voltage limits. Although a semiconductor device acts as a capacitor with its in-built junction capacitance when the reverse voltage starts to build up during turn-off, an additional parallel RC snubber branch normally has to be utilized to further reduce the overvoltage to a reasonable limit. Also the snubber is an essential part of power electronics. Snubber is small networks of parts in the power switching circuits whose function is to control the effects of circuit reactances.
snubber enhance the performance of the switching circuits and result in higher reliability, higher efficiency, higher switching frequency, smaller size, lower weight, and lower EMI[2].

The basic intent of a snubber is to absorb energy from the reactive elements in the circuit. The benefits of this may include circuit damping, controlling the rate of change of voltage or current or clamping voltage overshoot. In performing these functions a snubber limits the amount of stress which the switch must endure and this increases the reliability of the switch. When a snubber is properly designed and implemented the switch will have lower average power dissipation, much lower peak power dissipation, lower peak operating voltage and lower peak [2]. The basic function of a snubber is to absorb energy from the reactances in the power circuit. The first classification of snubber circuits is whether they absorb energy in controlling a voltage or a current. A capacitor is placed in parallel with other circuit elements will control the voltage across those elements. An inductor placed in series with other circuit elements will control the current through those elements. The following considerations can be used for rectifier diodes and phase control thyristor. Due to the assumption of soft recovery made on reverse recovery current waveforms, the evaluations may not be as appropriate for fast switching devices with heavy particle irradiation, and obviously they are not useful at all for turn-off devices such as IGBTs, IGCTs and GTOs in their normal operation modes, in which the current and voltage transients differ considerably from the situation described here [1].

It is the purpose of the present paper is to summarize the turn-off process of phase control thyristor and to present a design procedure for an optimized snubber in a specific application. For a given turn-off voltage and a given component voltage limit, the optimization will lead to minimum snubber capacitance, which normally also approximates the minimum in cost, space and power loss [1].
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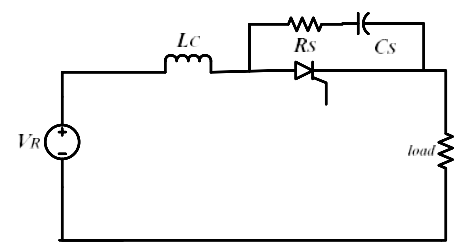


**Figure 1:** Simple equivalent RC Snubber circuit across thyristor.

Now, the voltage across the inductor is given by

$$V_R = L_C \frac{di}{dt} \quad (1)$$

Where, $V_R$ = Stationary voltage
$L_C$ = Commutation inducatance.

In actual practice; $R_S, C_S$ and the load circuit parameters should be such that $\frac{dv}{dt}$ across $C_S$ during its charging is less than the specified $\frac{dv}{dt}$ rating of the thyristor and discharge current at the turn on of thyristor is within reasonable limits. Normally $R_S$, $C_S$and load circuit parameters forms an undamped circuit so that $\frac{dv}{dt}$ is limited to acceptable values.

## 2. Thyristor Turn-off Model

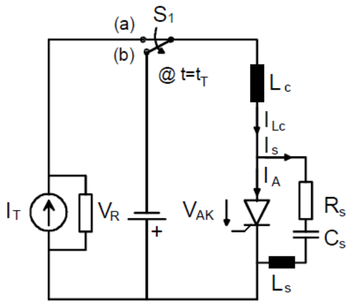


**Figure 2:** Equivalent circuit for turn-off of a thyristor

The typical equivalent circuit defining the turn-off transient for a phase control thyristor is given in Fig. 2 [1]. In the initial phase (t $\leq$0) the switch $S_1$ is in position (a), and the forward current $I_A$= $I_T$ flows through the Thyristor in the on-state. The snubber current $I_S$ is zero, and the snubber capacitor $C_S$ is uncharged. At t=$t_T$, $S_1$ is moved to position (b). The anode current now starts to decrease with $\frac{di}{dt} = -\frac{V_R}{L_C}$ as can be seen in Fig. 3 [1]. This condition continues even when the anode current reverses, because the semiconductor component still has a high amount of charge remaining for a few tens of microseconds and is able to conduct current. Now, the thyristor stops conducting, and due to the commutation inductance (needed to limit $\frac{di}{dt}$ in the thyristor) the thyristor voltage tends to jump to $V_R$ and overshoots. The snubber branch ($R_S$,$C_S$) now serves to reduce this overvoltage by conducting the snubber current $I_S = I_{LC} - I_A$ for a limited time itself, there by charging $C_S$. This reduces the overvoltage (and $\frac{dv}{dt}$ ), and it obviously also reduces the energy loss in the thyristor (because the momentary power is reduced), but it stores energy in the snubber capacitor. This energy has to be dissipated later in the snubber resistor when the thyristor turns on again or when the voltage returns to zero for other reasons.

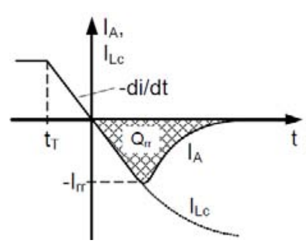


**Figure 3:** Current transients in a turn-off process.

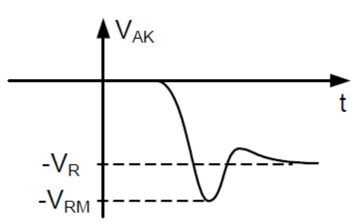


**Figure 4:** Voltage transients in a turn-off process.

For a given thyristor component, the reverse recovery current $I_{rr}$ and the reverse recovery charge $Q_{rr}$ are strongly dependent on $\frac{di}{dt}$ and junction temperature. These values are specified based on the condition that the thyristor device is in a stationary conducting state before the turn-off process starts. Their own dependence on the snubber is small and can normally be disregarded. The dependence on $I_T$ is virtually zero if the $\frac{di}{dt}$ is small enough to make the forward-current decay phase quasi-stationary, i.e. if $I_T/\frac{di}{dt}$ is at least a few times the carrier lifetime (typically a few hundred microseconds). Since the snubber capacitor has to integrate up the current difference $I_S = I_{LC} - I_A$ , the overvoltage is a function of the recovery waveform of the thyristor device for a given circuit configuration. Different waveforms with equal $I_{rr}$ and $Q_{rr}$ will lead to somewhat different overvoltage peak values, and this is the point where it becomes interesting to find an appropriate model for the reverse recovery current as a function of time. Stray inductance $L_S$ is negligible here [1].

In the present application note, the initial current decay slope $\left(\frac{di}{dt}\right)$, which is mathematically negative because the positive current decreases will as a simplification be used as a positive quantity in the formulas used.

## 3. Reverse Recovery Current model

It is known that due to different device designs, the reverse recovery current waveform can have different shapes. We traditionally distinguish between soft and hard recovery, and an extreme case is snap-off, as is shown in Fig. 5 [1]. Snap-off is generally not desired, since it often leads to excessive over voltages and induces ringing of the circuit. The type of recovery can be described by a softness factor s, defined as $s = \frac{(t_{rr}-t_a)}{t_a}$,where $t_{rr}$ is given by a straight line through the reverse recovery current peak and the point at -0.25 $I_{rr}$ on the decaying part of the recovery curve.
Thyristor is very often exhibit a soft recovery with s ~ 1.0 or somewhat larger. If $I_{rr}$ and $Q_{rr}$ are known for a device, a rough confirmation of this can be easily found by assuming a triangular shape for the recovery current, as shown in Fig. 5 Here,

$$s = \frac{2Q_{rr}\frac{di}{dt}}{I^2} - 1 \qquad (2)$$

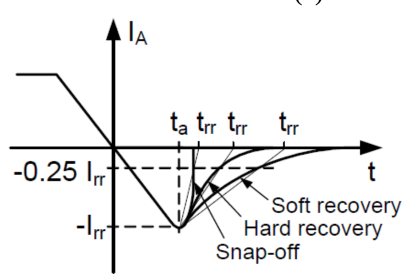


**Figure 5:** Types of reverse recovery waveforms.

This above equation is also a tool to verify if the data of $Q_{rr}$ and $I_{rr}$ given in a data sheet from a thyristor supplier fit together. In many cases, s does not vary significantly over a considerable range of $\frac{di}{dt}$or junction temperature. To obtain the reverse voltage overshoot $V_{RM}$, the current and voltage transients now have to be calculated, assuming a mathematically defined behaviour for the reverse recovery current waveform. There are two types of reverse recovery current waveform: Exponential recovery current model and hyperbolic secant recovery current model [1].

It is very common to utilize an exponential recovery current model for this purpose. And another model which includes the mathematically related hyperbolic secant functions.

The sharp $\frac{di}{dt}$ reversal in the reverse current waveform of exponential model is not very harmful; it will induce a voltage step of the order of a few volts if there is non-zero stray inductance $L_S$ (of the order of 1 μH) in the snubber circuit. For thyristor devices with a normal soft recovery and without extra tail currents, the approach of an exponential model is quite powerful and well suited to calculate the turn-off over voltages.

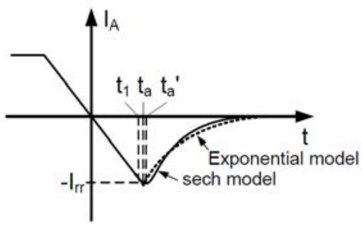


**Figure 6:** Comparison of exponential and sech models adjusted to exhibit the same $\frac{di}{dt}$, $Q_{rr}$, $I_{rr}$.

The transient reverse recovery analysis is obtained by utilizing thyristor turn-off model, so that an analytical solution of an RC snubber circuit values can be calculated. So in this paper we considered the under damped condition $\xi > 1$, $\xi = 0.5$.

## 4. Designing of RC snubber circuit

Depending on the degree of accuracy we will utilize different approaches. If a very high accuracy is needed, it would be best to take an actual measurement of a reverse recovery transient and to parameterize it according to the above hyperbolic secant or exponential function models, using the $Q_{rr}$ and $I_{rr}$ values known for the thyristor component under the expected operation conditions. The overvoltage waveform could then be calculated by using a circuit simulator like Pspice or by general calculation programs enabling the solution of differential equations. In Pspice, such a calculation circuit is quite easy to set up, as shown in Fig. 7 gives a measurement of the thyristor 5STP25L5200 with the Exponential recovery current model adjusted for equal $\frac{di}{dt}$, $Q_{rr}$ and $I_{rr}$ . The exponential model shows quite a difference from the measured behavior, both in the current and voltage waveforms [1].

For designing the snubber circuit, it is convenient to express the equations in terms of the following normalized parameters as

Initial current factor is $\chi = \frac{\text{intial energy in the inductor}}{\text{final energy in the capacitor}}$

$$\chi = \frac{\frac{1}{2} L_C I^2}{\frac{1}{2} C_S {V_R}^2} \qquad (3)$$

And

$$R_S = 2\xi\sqrt{\frac{L_C}{C_S}} \qquad (4)$$

Normalized peak voltage ratios $\frac{V_{RM}}{V_R}$ computed as a function of damping factor $\xi$ and initial current factor $\chi$

That is

$$\xi = \chi = \text{Function of } \left(\frac{V_{RM}}{V_R}\right) \qquad (5)$$

Where,

$V_{RM}$ is the peak overvoltage.

$V_R$ is the stationary voltage.

The design parameter with the voltage ratios $\frac{V_{RM}}{V_R}$ from which snubber may be designed to give a specified $\frac{dv}{dt}$ using minimum capacitance. Note that minimum $\frac{dv}{dt}$ is obtained with less damping than required to minimize the voltage spike. The RC snubber design procedure explains below [1],

It is assumed that the stationary voltage $V_R$ and the Commutation inductance $L_C$ are known.

The ratio $\frac{V_R}{L_C}$ then gives the $\frac{di}{dt}$, from the thyristor data sheet fig. 8. we read the $Q_{rr}$ value at this $\frac{di}{dt}$ .

Knowing the desired ratio $\frac{V_{RM}}{V_R}$ , the minimum capacitance $C_S$ can then be found by reading $\frac{Q_{rr}}{C_S V_R}$ at the maximum of the appropriate curve in Fig. 10.

Since $C_S$ is known now, reading the value $\frac{R_S^2 \; C_S}{L_C}$ on the Horizontal axis then yields the optimum value of Rs.

Calculation of RC snubber can be obtained by considering 5STP25L5200 ABB Thyristor model using Pspice simulation analysis is given by

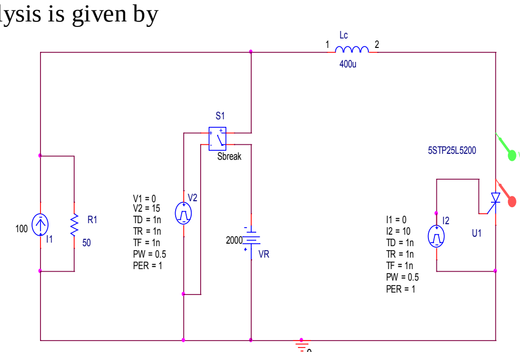


**Figure 7:** Turn-off model of 5STP25L5200 ABB Thyristor model using Pspice simulation

Assume $V_R = 2000$, $L_C = 400\mu$ .and

We know from the fig. 1

$$V_R = L_C \frac{di}{dt}$$

$$\frac{di}{dt} = \frac{2000}{400} = 5 \text{ A/μs}$$

From the 5STP25L5200ABB thyristor data sheet we can read the $Q_{rr}$ value at this $\frac{di}{dt}$

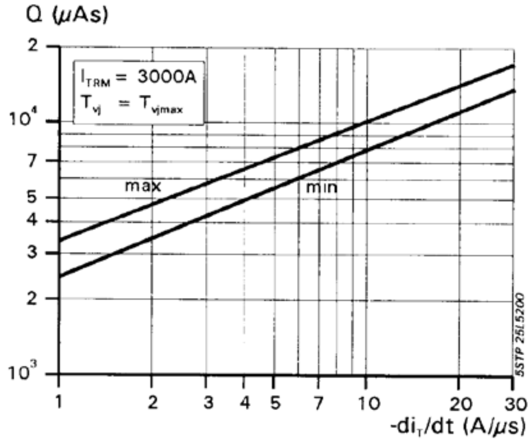


**Figure 8:** Reverse recovery charge versus decay rate of on state current of the 5STP25L5200 data sheet

Here we got the value of $Q_{rr} = 7200\mu As$ at $\frac{di}{dt} = 5\ A/\mu s$. The output of the Pspice simulation result is given by

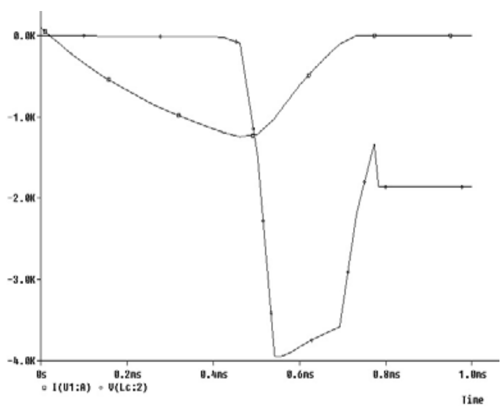

**Figure 9:** Pspice simulation result of reverse recovery current and reverse peak over voltage.

From the output waveform, the value of the reverse peak over voltage is can be read as $V_{RM} = 3900$.

The ratio of the reverse voltage is $\frac{V_{RM}}{V_R} = \frac{3900}{2000} = 1.95 \cong 2$

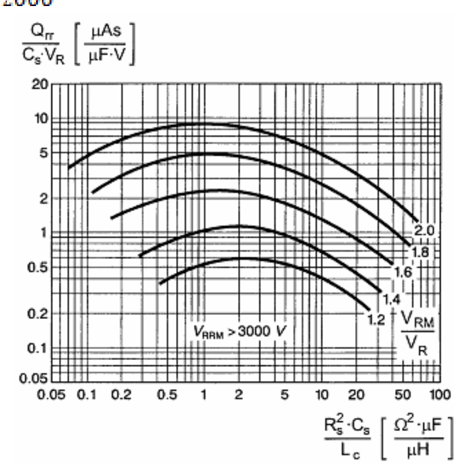


**Figure 10:** Curves for determining the optimum RC snubber values of ABB Thyristor data sheet range above 3000v

Curves for determining the optimum RC snubber values of ABB phase control thyristor.

The curves are valid for thyristors with $V_{RM}$ ratings above 3000V.This curve is can be obtained from the 5STP25L5200 ABB thyristor data sheet. And we know that

$$\frac{di}{dt} = Q_{rr} = C_S V_{RM} \tag{6}$$

$$Q_{rr} = \frac{C_S V_{RM} \times V_R}{V_R}$$

This implies that $\frac{V_{RM}}{V_R} = \frac{Q_{rr}}{C_S V_R}$

The value of the capacitance is can be calculated by reading the maximum value of the y-axis at the ratio of $\frac{V_{RM}}{V_R} = 2$ is equivalent to $9\,\frac{\mu As}{\mu F V}$ from the fig. 10

$$9 = \frac{7200}{C_S 2000}$$

$$C_S = 0.4\mu F$$

And again from the fig. 10, maximum value of the x-axis at the ratio of $\frac{V_{RM}}{V_R} = 2$ is equivalent to $1.5\,\frac{\Omega^2 \mu F}{\mu H}$.

From the equation 5

$$R_S = 2\xi \sqrt{\frac{L_C}{C_S}}$$

Here ξ damping is considered as 0.5 under damped condition and also it is the function of the reverse voltage ratios $\frac{V_{RM}}{V_R}$.

So

$$\frac{V_{RM}}{V_R} = \frac{R_S^2 C_S}{L_C}$$

$$1.5 = \frac{R_S^2 0.4}{400}$$

$$R_S = 39\Omega$$

## 5. Snubber Component Selections

In the earlier paragraphs it was shown how the resistance and capacitance values for the RC snubber can be determined. The calculated values can though seldom be directly realized with real components. To reduce costs, standard components are normally selected and they are available only in certain steps and with certain tolerances. Since the resistors often are available in finer steps than the capacitors, we recommend determining the capacitance value first. The capacitance is chosen as the standard value the supplier offers and which is the closest to the calculated capacitance, having in mind that a higher capacitance value gives a higher safety margin at the cost of higher resistor losses and that a lower value, considering also the component tolerances, gives a higher voltage peak than that calculated. By selecting a capacitance other than that which is calculated, the ratio $R_s^2 C_s / L_C$ is changed and therefore a check should be made as to whether a different resistance value should be chosen to minimize the overvoltage. The calculated resistance is then chosen as the closest available standard value. The difference in overvoltage resulting from selecting a resistance slightly different from the calculated one can normally is disregarded [1].

### 5.1. Voltage Ratings of Snubber Capacitor and Snubber Resistor

When selecting the capacitor, a number of different voltage ratings have to be considered. The main parameters are the rms and the repetitive voltage ratings. The rms voltage the capacitor is dependent on the application and on the way it is used. For a three phase bridge, the rms voltage will be a function of the firing angle. It reaches its maximum for firing angles of 0° or 180 ° at 0.90 times the sinusoidal rms voltage at the 3-phase input of the bridge. Some capacitor suppliers do not rate their capacitors with an rms current but either with a "rated" AC voltage, which is then, defined as either the maximum repetitive peak voltage in operation or as the maximum repetitive peak-to-peak voltage. Peak voltages for this consideration do not include the relatively short transient switching over voltages discussed above. It is important to consider the switching over voltages separately. Capacitor suppliers often specify the real peak voltage limit as a function of the percentage of time this voltage is applied with respect to the repetition time period [1].

## 6. Conclusions

We have shown that RC snubber circuits can be utilized to limit the reverse overvoltage during turn-off of thyristor. They also have an influence on the power loss in the thyristor but they cause losses of their own due to the need to discharge the capacitor before the next thyristor turn-off.

We have also shown that by using specification data of $Q_{rr}$ and $I_{rr}$ at a given $\frac{di}{dt}$, models for the reverse current waveform can be set up and will allow more accurate calculation of the reverse overvoltage peak amplitude, the thyristor turn-off loss.

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