APPLICATION NOTE 5SYA 2020-03

Design of RC-snubbers for phase control applications

Semiconductor devices are very powerful in controlling high currents and voltages. Nevertheless, they are very susceptible to violations of the safe-operating conditions which may lead to their failure. When a phase control device must 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.

1. Introduction

A semiconductor device has a built-in junction capacitor. However, when a reverse voltage starts to rise during the turn-off phase, this capacitance is insufficient to reduce any overvoltage. An additional parallel RC-snubber is then needed to reduce the overvoltage to a reasonable limit.

Snubber component design depends on the operating conditions including commutation inductance, voltage and di_T/dt during turn-off. Other factors to consider include the semiconductor's reverse current waveform during operation and its circuit conditions. The snubber also influences the semiconductor's turn-off losses.

This document explains the turn-off process of phase control devices. It outlines a design procedure for optimizing a snubber for a specific application.

The document does not cover series or parallel connected phase-controlled devices. Situations requiring control of a transient voltage or homogenous current sharing, needs separate investigation[1)].

The following considerations can be used for rectifier diodes and phase control thyristors. 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.

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2. Device turn-off process

The typical equivalent circuit defining the turn-off transient for a phase control device is given in Fig. 1 (phase control thyristor in this case):

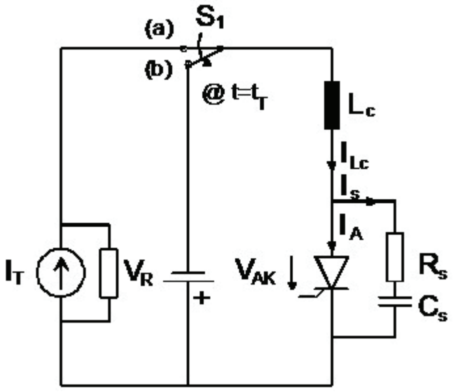

Fig. 1 Equivalent circuit for turn-off of a rectifier diode or a phase control thyristor

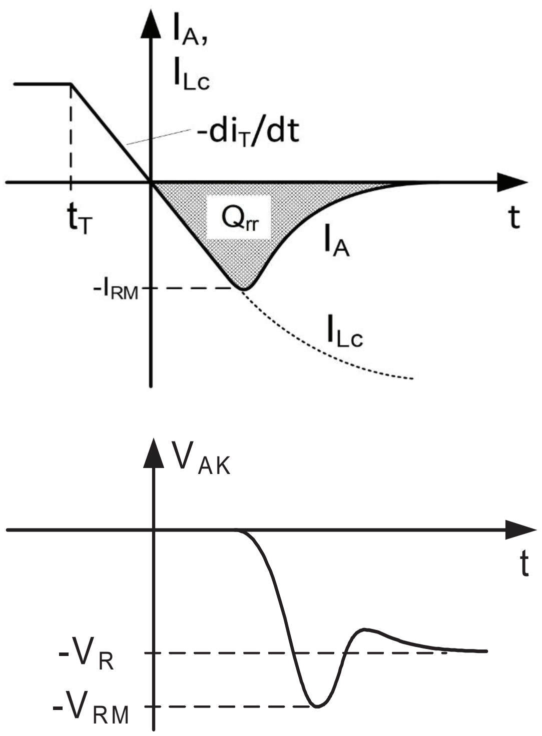

Fig. 2 Current and voltage transients in a turn-off process according to Fig. 1

Initial phase, $t \leq t_T$

- Switch S_1 is in position (a) – see Fig. 1.
- Forward current $I_A = I_T$ and flows through the PCT in the on-state.
- Snubber current I_s is zero.
- Snubber capacitor C_s is uncharged.

At $t = t_T$

- S_1 is moved to position (b) – see Fig. 1.
- Anode current now starts to decrease with $di_T/dt = -V_R/L_c$ – see Fig. 2. This condition continues, even when the anode current reverses. This is because semiconductor component is still highly charged for a few microseconds and can conduct current.
- Semiconductor stops conducting.
- Due to commutation inductance (needed to limit di_T/dt in the semiconductor) the semiconductor voltage jumps to V_R and to overshoot to V_{RM}.
- Snubber branch R_s, C_s now reduces this overvoltage by conducting current $I_s = I_{Lc} - I_A$ for a limited time, thereby charging C_s.
- This reduces overvoltage (and dv/dt). It also reduces energy loss in semiconductor, as momentary power is reduced.
- Energy is stored in the snubber capacitor. This energy must be dissipated later in the snubber resistor when the semiconductor turns on again or when the voltage returns to zero for other reasons.
- For a given semiconductor component:
  - reverse recovery current I_{RM} and reverse recovery charge Q_{rr} are strongly dependent on di_T/dt and junction temperature.
  - values specified based on condition that device is in a stationary conducting state before turn-off process starts.
  - their own dependence on the snubber is small and can normally be disregarded.
  - dependence on I_T is virtually zero if di_T/dt is small enough to make forward-current decay phase quasi-stationary, i.e. if I_T divided by di_T/dt is at least a few times the carrier lifetime (typically a few hundred microseconds).
  - since snubber capacitor must integrate up the current difference $I_s = I_{Lc} - I_A$, the overvoltage is a function of recovery waveform of the semiconductor device for a given circuit configuration.

Note: In this document, the initial current decay slope "di_T/dt" - which is mathematically negative because the positive current decreases - will be used as a positive quantity throughout the formulas.

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3. Snubber design for an individual semiconductor

3.1. Snubber capacitor “C_S”

In an undamped series resonant circuit like figure 3, the maximum reverse voltage V_{RM} can be estimated [3)]:

Eqn. 1 [3)]

$$V_{RM} = v_{C_{S,max}} = V_R[1 + \sqrt{1 + \frac{C_{base}}{C_S}}]$$

where a baseline capacitance used to design snubber capacitor C_s can be introduced as follows:

Eqn. 2 [3)]

$$C_{base} = L_c * \left[\frac{I_{RM}}{V_R}\right]^2$$

The thyristor overvoltage ratio as a function of C_S can be expressed as:

Eqn. 3 [3)]

$$\frac{V_{RM}}{V_R} = 1 + \sqrt{1 + \frac{C_{base}}{C_S}}$$

Fig. 4 shows that the maximum reverse voltage decreases only slightly by increasing capacitive snubber C_S beyond the baseline capacitance C_{base}. However, the total energy dissipation in the resistive snubber increases almost linearly with C_S. Therefore, a capacitive snubber with C_S in a range close to C_{base} would be used as optimum C-snubber.

3.2. Snubber resistor “R_S”

Including the thyristor snubber resistance R_s, the equivalent baseline circuit Fig. 3 transforms into Fig. 5.
Fig. 5 shows a damped series-resonant circuit, where the oscillations are damped by R_S.
The maximum thyristor reverse voltage, V_{RM}, depends on the used values of R_S and C_S. For a selected C-snubber, determined by Eqn. 2, the maximum thyristor reverse voltage, V_{RM}, depends, in addition, on R_s. To normalize R-snubber, a baseline resistance R_{base} is introduced in Eqn. 4:

Eqn. 4 [3)]

$$R_{base} = \frac{V_R}{I_{RM}}$$

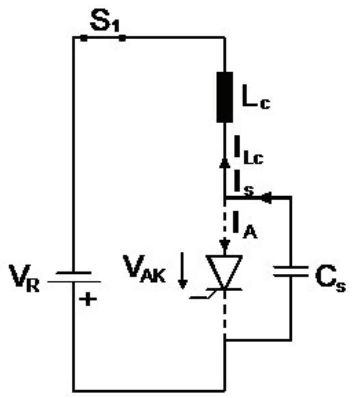

Fig. 3 Equivalent circuit for turn-off of a phase control thyristor (R_s=0 Ω)

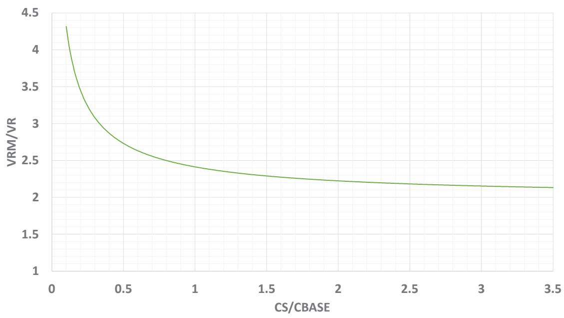

Fig. 4 The maximum reverse voltage as a function of the capacitive snubber C_S (R_s=0 Ω)

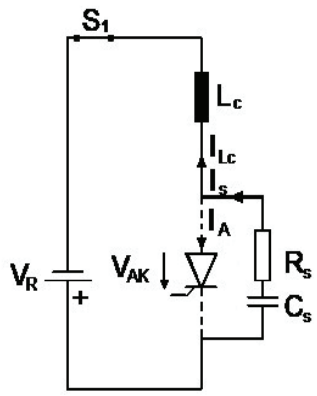

Fig. 5 Equivalent circuit for turn-off of a phase control thyristor

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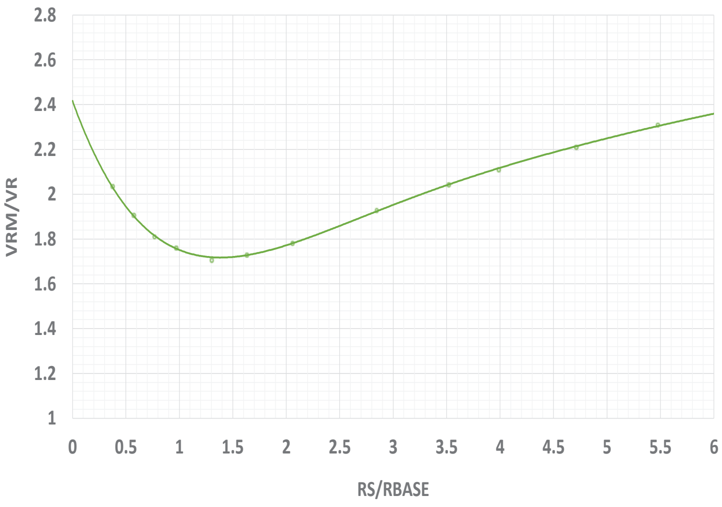

Fig. 6 Maximum reverse voltage across thyristor as a function of resistive snubber R_s for a fixed capacitive snubber C_S=C_{base}

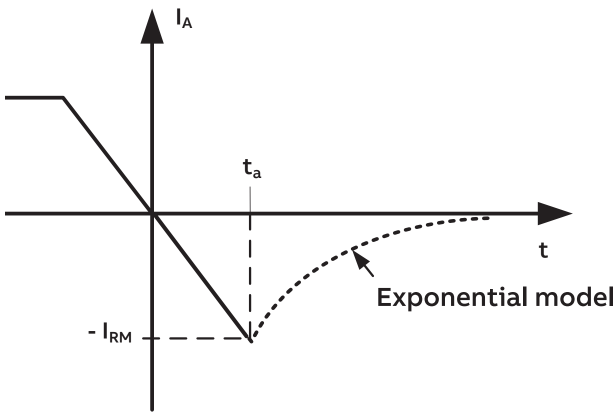

Fig. 7 Exponential model

Fig. 6 shows the maximum thyristor reverse voltage, as a function of the normalized R-snubber. According to Eqn. 3, the overvoltage ratio for a fixed value of C-snubber, C_S= C_{base} at R_S = 0 Ω, is calculated V_{RM}/V_R = 2.41. The thyristor's minimum stress - or the optimum value of the R-snubber is located at the curve's lowest point. This is where the thyristor overvoltage ratio V_{RM}/V_R has the smallest value.

In the application, the thyristor reverse recovery current can be assumed to decay exponentially, as shown in Fig. 7. This behavior can be simulated by replacing the thyristor with a time varying current source, as shown in Fig. 8.

The exponential current model assumes that the reverse current is linear up to t = t_a and I_A = -I_{RM}, with a slope of -di_T/dt, and it decays with an exponential function as follows:

$$I_A(t) = -I_{RM} * e^{-\frac{t-t_a}{\tau}} \qquad \text{Eqn. 5}$$

where τ, the decay time constant and t_a is known from di_T/dt and I_{RM}, and τ can be mathematically approached by using Q_{rr}:

$$\tau = \frac{Q_{rr}}{I_{RM}} - \frac{I_{RM}}{2*\frac{di_T}{dt}} \qquad \text{Eqn. 6}$$

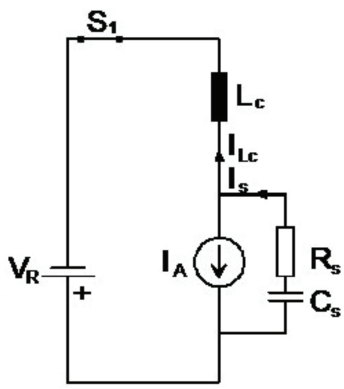

Fig. 8 Equivalent circuit for turn-off of a phase control thyristor, soft reverse recovery

The analysis can be carried out by computer simulation or experimental measurements. The results show that the snubber design remains essentially the same as before.

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3.3. R-snubber design charts for ABB standard PCT products

The voltage class of ABB standard PCTs are:

- 1800 V, 2800 V, 4200 V, 5200 V, 6500 V, 7200 V and 8500 V.

Depending on the voltage class, the PCT housing size ranges from the smallest, “D”, to the largest, “Y”. Snubber design charts for each voltage class are listed in the following. Each chart contains four snubber design curves, based on experimental results, for four different values of C-snubber:

- $C_S = 0.2*C_{base}$
- $C_S = 0.5*C_{base}$
- $C_S = C_{base}$
- $C_S = 2*C_{base}$

We recommend the optimum for a first RC snubber design, since it is the most efficient RC snubber for the application. Additionally, the user should use the solid R-Snubber design curves (on the right side of the optimum), in order to reduce the discharge current from the C-Snubber when turning on the device again. For an optimum RC-snubber design, it is recommended that the optimum damping R-snubber is used at the lowest point on the corresponding curve to the corresponding C-snubber.

Figs. 9 to 15 represent the worst case of V_{RM}/V_R with regard to a wide application range of di_T/dt and T_{vj} of the respective PCTs. Experiments conclude that the influence of commutation voltage V_R, irradiation and wafer size, regarding the maximum thyristor overvoltage V_{RM}, can be neglected. The following design curves applied, based on measured results.

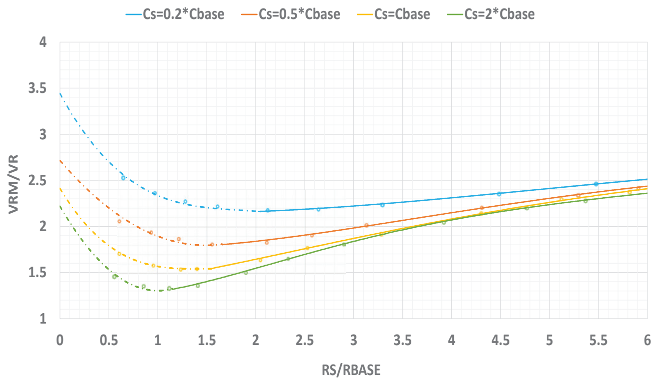

Fig. 9 Snubber design chart for voltage class 1800 V

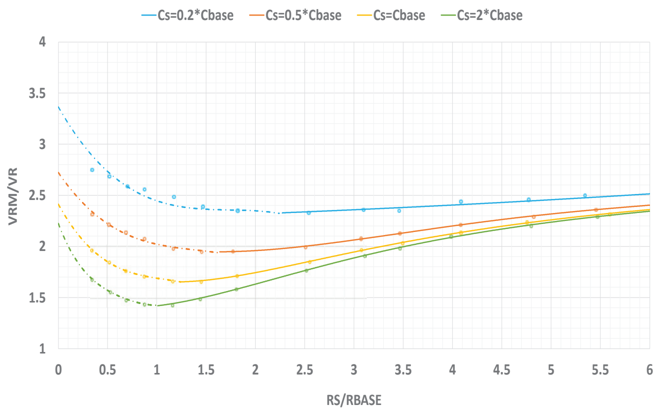

Fig. 11 Snubber design chart for voltage class 4200 V

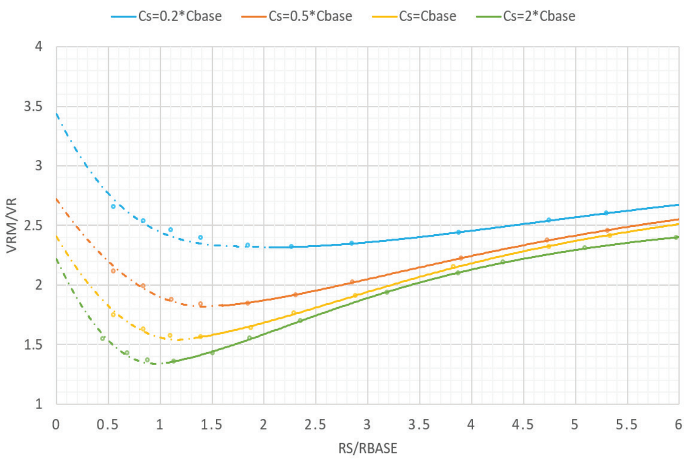

Fig. 10 Snubber design chart for voltage class 2800 V

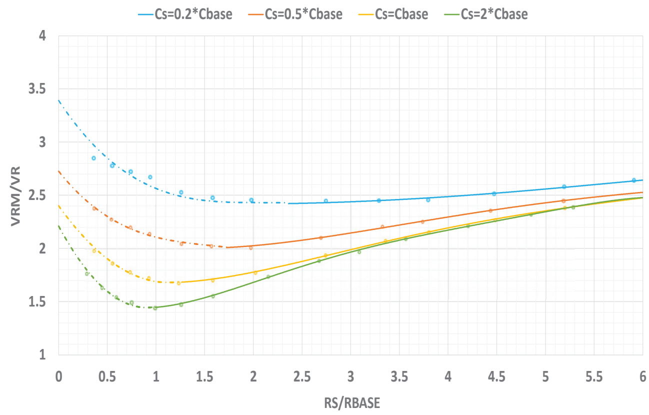

Fig. 12 Snubber design chart for voltage class 5200 V

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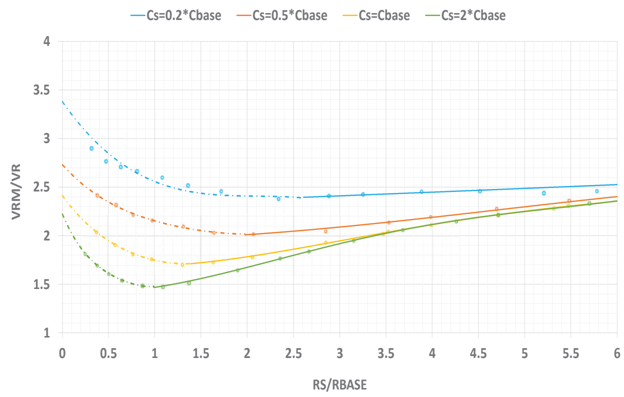

Fig. 13 Snubber design chart for voltage class 6500 V

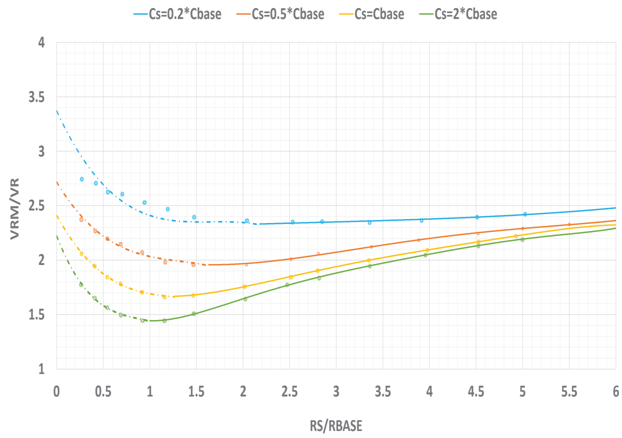

Fig. 14 Snubber design chart for voltage class 7200 V

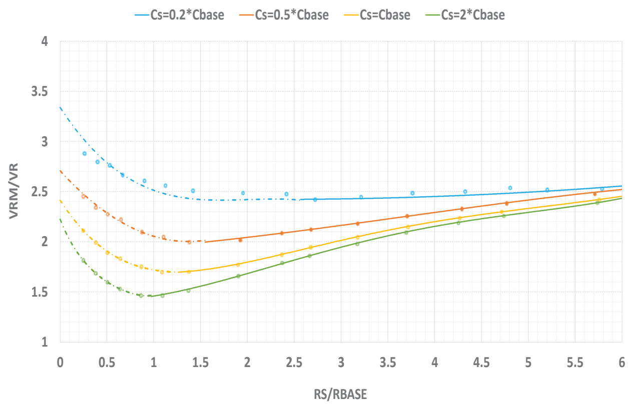

Fig. 15 Snubber design chart for voltage class 8500 V

4. Snubber operation in 6-pulse converter bridge configuration

The following discussion focuses on thyristors, rather than on diodes. This is because thyristors are a generalization of both device types. The freedom in selecting firing angles is not an option for diodes. Furthermore, the overvoltage considerations for thyristor bridges with full firing angle control and diode bridges are somewhat different.

Any influences from stray inductances in the snubber branches are neglected. This is acceptable, provided low inductive RC-snubber design is used.

In applications such as AC switches, the thyristors have individual RC-snubbers that do not interact with other RC-snubbers at turn-off. For the common 6-pulse bridge configuration, the RC-snubbers will communicate with each other at turn-off, if each thyristor has its own RC-snubber. Here we look at the influence, at turn-off, of thyristor 1 in Fig. 16.

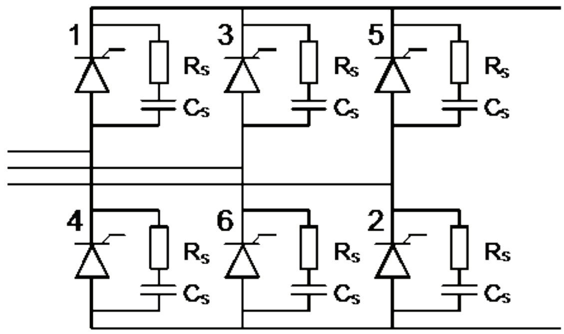

Fig. 16 6-pulse thyristor converter bridge configuration with individual RC-snubbers for each semiconductor

At turn-off of thyristor 1, thyristors 2 and 3 are conducting and are thus short-circuiting their RC-snubbers. However, thyristors 4, 5 and 6 are blocking and thus their RC-snubbers influence the turn-off of thyristor 1. For this turn-off phase we get an equivalent circuit as shown in Fig. 17.

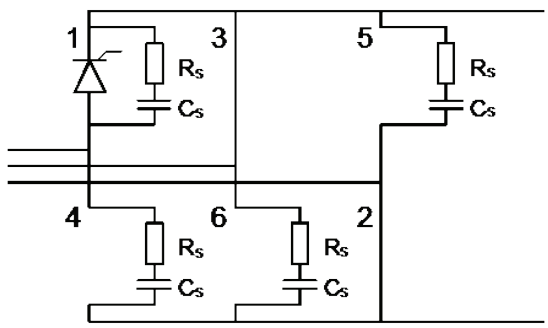

Fig. 17 Equivalent circuit when thyristor 1 turns off

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In Fig. 17, the RC-snubbers of thyristors 5 and 6 are now connected in parallel. This parallel connection is in series with the RC-snubber of thyristor 4.
Simplifying Fig. 17 we arrive at Fig. 18.

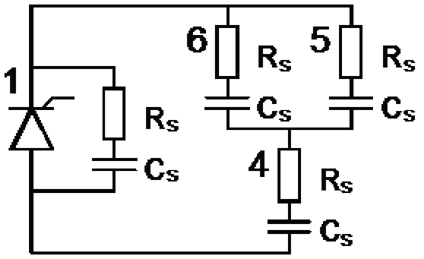

Fig. 18 Simplified equivalent circuit during turn-off of thyristor 1

Using standard formulae for parallel and series connection of resistors and capacitors, thyristor 1 at turn-off sees an RC-snubber with equivalent resistance and capacitance R_{eq} and C_{eq} which can be expressed by the component values R_s and C_s as:

$$R_{eq} = \frac{3}{5} R_s \qquad \text{Eqn. 7}$$

and

$$C_{eq} = \frac{5}{3} C_s \qquad \text{Eqn. 8}$$

For calculation of the overvoltage peak for 6-pulse bridges, R_{eq} and C_{eq} should be used in the formula and the discrete component values R_s and C_s can then be calculated from Eqn. 7 and 8.
Due to the nature of the 6-pulse bridge, the thyristor and the snubber circuit will see voltage spikes coming from the commutation of the other thyristors in the bridge. The voltage spikes depend on the firing angle and will be largest at a firing angle of 90°. Thyristor 1, for example, will in addition to its own turn-on and turn-off, also see overvoltage spikes from the turn-off of thyristors 3, 4 and 6. The voltage spikes from turn-off of 4 and 6, however, will not affect the voltage stress of the thyristor, since they appear at low voltage levels. The turn-off of thyristor 3 will not affect the voltage stress of the device either, but it has a significant impact on the RC-snubber losses.

5. Snubber design calculation example

An example for calculating the snubber is as follows: The B6 pulse bridge shown in Fig. 19 features phase control thyristors of voltage class 6500 V, 5STP 26N6500.
Following snubber design requirements from the application are given:

- The maximum reverse voltage commutation is V_R = 3000 V and the maximum overvoltage shall be V_{RM} < 6300 V as design requirement
- Therefore, $V_{RM}/V_R < 2.1$
- The commutation inductance $L_c = 2{*}L_s = 500\ \mu H$, therefore the $di_T/dt = V_R/L_c = 6\ A/\mu s$

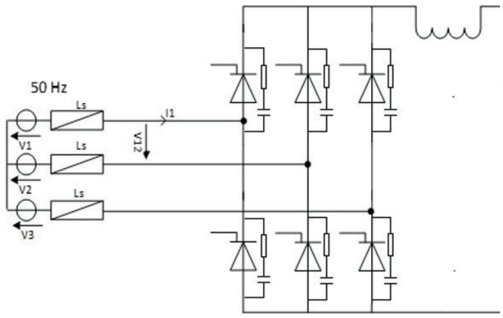

Fig. 19 6 pulse thyristor rectifier with PCTs 5STP 26N6500

The value of the peak reverse recovery current is to read out at di_T/dt = 6 A/µs from the data sheet max-curve of I_{RM} vs. $-di_T/dt$ (Fig. 20): I_{RM} = 250 A.

Selecting $C_S' = 0.5 * C_{base}$ yields:

$$C_S' = 0.5 * C_{base} = 0.5 * L_c * \left[\frac{I_{RM}}{V_R}\right]^2 \cong 1.7\ \mu F$$

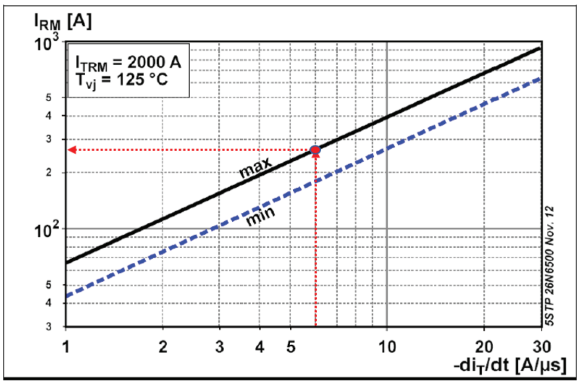

Fig. 20 Peak reverse recovery current vs. decay rate of on-state current at V_R = 200 V (Fig.9 in the data sheet of 5STP 26N6500)

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From the snubber design curve in Fig. 21, the resulting value of R-snubber corresponding to V_{RM}/V_R = 2.1 and C_S' = 0.5 * C_{base} is found to be:

$$R'_S = 2 * R_{base} = 24\ \Omega$$

Where the baseline resistance is:

$$R_{base} = \frac{V_R}{I_{RM}} = 12\ \Omega$$

Under consideration of the worst-case thyristor turn-off voltage transient, and according to Eqn. 7 and 8, the individual RC-snubber components are:

$$C_S = \frac{3}{5} * C'_S \cong 1.1\ \mu F$$

$$R_S = \frac{5}{3} * R'_S \cong 40\ \Omega$$

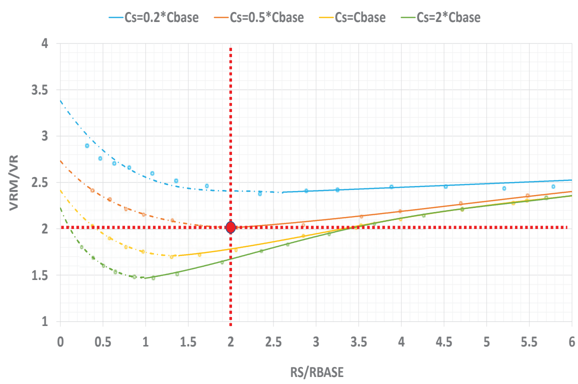

Fig. 21 Snubber design chart for voltage class 6500 V

6. Conclusions

Electrical stresses (reverse overvoltage) on a phase control device or rectifier diode caused during switching can be reduced using snubber circuits, to levels that are within the device's electrical ratings.

Snubber circuits also influence the power loss in the semiconductor. However, they cause losses of their own due to the need to discharge the capacitor before the next semiconductor turn-off. Design and snubber component selection, also for 6-pulse bridge design, are described in detail.

This document shows that, by using RC-snubber design charts and corresponding data sheet, optimum RC-snubber values can be determined as a start value, which may be further optimized by user. This is independent of the used current decay slopes, commutation voltages, wafer sizes, operating junction temperatures and wafer irradiations.

The maximum thyristor overvoltage value measured when the snubber is designed in this way, should always be below the curve values, yet reasonably close to them.

Depending on the influence of these parameters and tolerance of the snubber components, the real thyristor overvoltage ratio can be varied and is out of scope of this application note.

This application note is for typical power grid applications, special applications require specific hardware tests.

7. References

1) 5SYA 2091 "Parameter selection of high power semiconductor devices for series and parallel connection", www.hitachiabb-powergrids.com/semiconductors

2) 5SYA 2055 "Switching losses for phase control and bi-directionally controlled thyristors", www.hitachiabb-powergrids.com/semiconductors

3) "Diode and thyristor turn-off snubbers simulation by KREAN and an easy to use design algorithm," IEEE IAS Proc., 1988

8. Revision history

Version	Change	Authors
02		Jürg Waldmeyer Björn Backlund
03	Snubber Design Method	Jieliang Zhang

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