# OPTIMUM SNUBBERS FOR POWER SEMICONDUCTORS

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## Abstract

It is generally necessary to connect an R-C snubber across a power rectifier or thyristor to absorb the energy associated with the recovery current of the device and limit the resulting voltage spike and rate of rise dv/dt. For a given snubber capacitance, it is shown that there is an optimum damping resistance which minimizes the peak voltage but a lower resistance is required to minimize the average dv/dt to the peak. Design procedures are derived for selecting the capacitance and optimum resistance to limit the peak voltage or dv/dt to specified values. The device recovery current is trapped in circuit inductance and its energy must be dissipated, while the snubber produces additional losses as the price of performing its limiting function.

## General Equations of Recovery Voltage Transient

For analysis of the recovery voltage transient appearing across a semiconductor rectifier diode or thyristor device, a power converter can usually be reduced to an equivalent circuit of the form shown in Fig. 1. A voltage E, which can be assumed steady throughout the transient, is applied to a series R-C-L circuit. The voltage e across the snubber resistance and capacitance in series appears as recovery voltage on the semiconductor device. The initial capacitor voltage is zero, but an initial current I is present in the circuit. This is the peak reverse recovery current in the device, which becomes established in the inductance L and is forced to transfer to the R-C path when the device blocks. Blocking is assumed to occur in a short interval, which is certainly the case for snap-off diodes and a reasonable approximation for most other devices. Time zero of the transient is the instant when the device blocks. The initial value of e is IR. An ideal recovery transient is shown in Fig. 2.

The peak recovery current I for a given device is a function of temperature, the previous forward current before application of the commutating voltage E, and the rate di/dt which is equal to E/L. Typical or maximum values of recovery current (or the recovered charge, from which the current can easily be calculated) are included in many device specifications as functions of these parameters [1].

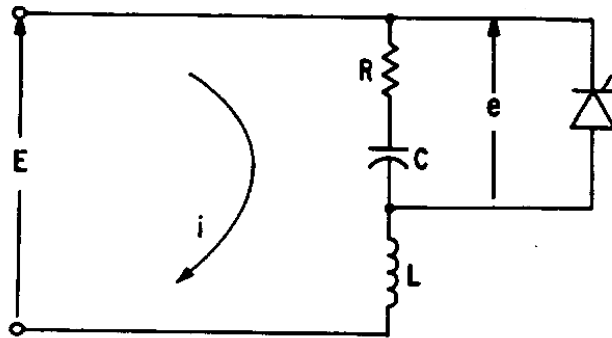The general Laplace transforms for the current i and the voltage e are



Fig. 1 Equivalent Circuit of Snubber

$$i(s) = \frac{\frac{E}{L} + sI}{s^2 + \frac{R}{L}s + \frac{1}{LC}} \tag{1}$$

$$e(s) = -\frac{s(E-RI) - \frac{I}{C}}{s^2 + \frac{R}{L}s + \frac{1}{LC}} + \frac{E}{s} \tag{2}$$

The general solutions of these equations will now be presented. The parameters $\omega_0$ and $\alpha$ are defined as follows.

Un-damped natural frequency (radians/sec):

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{3}$$

Decrement factor:

$$\alpha = \frac{R}{2L} \tag{4}$$

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

Initial current factor:

$$\lambda = \frac{I}{E}\sqrt{\frac{L}{C}} \tag{5}$$

Damping factor:

$$\zeta = \frac{R}{2\sqrt{L/C}} = \alpha/\omega_0 \tag{6}$$

Note that
$$\chi^2 = \frac{\frac{1}{2}LI^2}{\frac{1}{2}CE^2} = \frac{\text{Initial energy in inductance}}{\text{Final energy in capacitor}} \qquad (7)$$

## Case I Under-damped condition, $\zeta < 1$

This is the case of most practical importance, since it includes the optimum design of the snubber circuit. The angular frequency of the damped oscillations is given by

$$\omega = \sqrt{\omega_o^2 - \alpha^2} = \omega_o \sqrt{1 - \zeta^2} \qquad (8)$$

The inverse transform of (2) yields

$$e = E - (E - RI)(\cos \omega t - \frac{\alpha}{\omega} \sin \omega t)\, \epsilon^{-\alpha t}$$
$$+ \frac{I}{C\omega} \sin \omega t \, \epsilon^{-\alpha t} \qquad (9)$$

Differentiating (9)

$$de/dt = (E - RI)(2\alpha \cos \omega t + \frac{\omega^2 - \alpha^2}{\omega} \sin \omega t)\, \epsilon^{-\alpha t} + \frac{I}{C}(\cos \omega t - \frac{\alpha}{\omega}\sin \omega t)\epsilon^{-\alpha t} \qquad (10)$$

The initial voltage and slope can be deduced by inspection of the circuit Fig. 1, or obtained by setting $t = 0$ in (9) and (10). Note that the result is the same for critical or over-damping.

$$\left(\frac{e}{E}\right)_o = \frac{RI}{E} = 2\zeta\chi \qquad (11)$$

$$\left(\frac{de}{dt}\right)_o = (E - RI)\, 2\alpha + \frac{I}{C} \qquad (12)$$

$$= \frac{(E - RI)R}{L} + \frac{I}{C} \qquad (13)$$

$$= E\omega_o\, (2\zeta - 4\zeta^2\chi + \chi) \qquad (14)$$

If this initial slope is not positive, then the initial recovery voltage given by (11) is the maximum. However, if

$$2\zeta - 4\zeta^2\chi + \chi > 0 \qquad (15)$$

$$\text{or} \quad \zeta < \frac{1 + \sqrt{1 + 4\chi^2}}{4\chi} \qquad (16)$$

the slope is positive and the recovery voltage rises to a peak at a time $t_1$ which can be obtained by setting (10) equal to zero, yielding

$$\tan \omega t_1 = -\frac{(E - RI)\, 2\alpha + \frac{I}{C}}{(E - RI)\frac{\omega^2 - \alpha^2}{\omega} - \frac{I\alpha}{C\omega}} \qquad (17)$$

$$= -\frac{(2\zeta - 4\zeta^2\chi + \chi)\sqrt{1 - \zeta^2}}{1 - 3\zeta\chi - 2\zeta^2 + 4\zeta^3\chi} \qquad (18)$$

$$= f(\zeta, \chi) \quad \text{(definition of function)} \qquad (19)$$

$$t_1 = \frac{1}{\omega}\tan^{-1} f(\zeta, \chi) \qquad (20)$$

$$= \frac{\tan^{-1} f(\zeta, \chi)}{\omega_o \sqrt{1 - \zeta^2}} \qquad (21)$$

where the angle is in the first or second quadrant, depending upon whether the function $f(\zeta, \chi)$ is positive or negative respectively.

Substituting the value of $t_1$ from (21) into (9), the value $E_1$ of the peak recovery voltage is obtained

$$E_1 = E + \epsilon^{-\alpha t_1}\sqrt{(E - RI)^2 + \frac{2\alpha(E - IR)\,I}{\omega_o^2}\cdot\frac{I^2}{C} + \frac{I^2}{\omega_o^2 C^2}} \qquad (22)$$

The normalized peak voltage can be reduced to a function of $\zeta$ and $\chi$, defined as $p(\zeta, \chi)$

$$p(\zeta, \chi) = \frac{E_1}{E} = 1 + \exp\left\{-\frac{\zeta}{\sqrt{1 - \zeta^2}}\tan^{-1}\left[f(\zeta, \chi)\right]\right\}\sqrt{1 - 2\zeta\chi + \chi^2} \qquad (23)$$
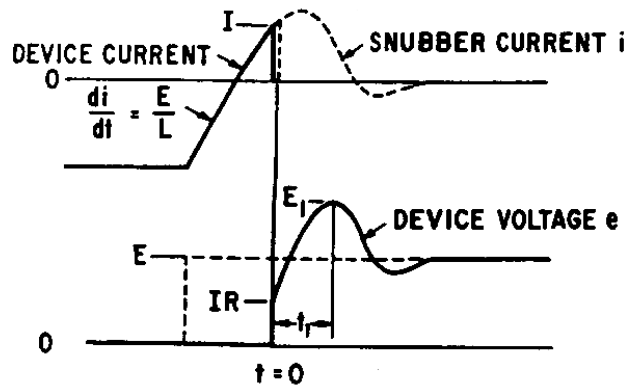


Fig. 2  Idealized Recovery Transient

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The average rate of rise of voltage to this peak value is

$$\left(\frac{dv}{dt}\right)_{avg} = \frac{E_1}{t_1} = E\omega_o \frac{p(\zeta, \chi)\sqrt{1-\zeta^2}}{\tan^{-1} f(\zeta, \chi)} \quad (24)$$

$$= \frac{E^2}{LI} \frac{\chi\, p(\zeta, \chi)\sqrt{1-\zeta^2}}{\tan^{-1} f(\zeta, \chi)} \quad (25)$$

## Case IA. No damping, ζ = 0

The equations for this special case can be obtained from the general equations for under-damping by setting R, α and ζ equal to zero, while ω becomes $\omega_o$.

$$e = E(1 - \cos\omega_o t) + \frac{I}{C\omega_o}\sin\omega_o t \quad (26)$$

$$de/dt = E\omega_o \sin\omega_o t + \frac{I}{C}\cos\omega_o t \quad (27)$$

$$\left(\frac{de}{dt}\right)_o = \frac{I}{C} = E\omega_o\chi \quad (28)$$

$$\tan\omega_o t_1 = -\frac{I}{E\omega_o C} = -\chi \quad (29)$$

$$t_1 = \frac{\pi - \mathrm{Tan}^{-1}\chi}{\omega_o} \quad (30)$$

$$E_1 = E + \sqrt{E^2 + \left(\frac{I}{\omega_o C}\right)^2} \quad (31)$$

$$p(0, \chi) = \frac{E_1}{E} = 1 + \sqrt{1+\chi^2} \quad (32)$$

$$\left(\frac{dv}{dt}\right)_{avg} = \frac{E_1}{t_1} = E\omega_o \frac{1+\sqrt{1+\chi^2}}{\pi - \mathrm{Tan}^{-1}\chi} \quad (33)$$

$$= \frac{E^2}{LI} \frac{\chi(1+\sqrt{1+\chi^2})}{\pi - \mathrm{Tan}^{-1}\chi} \quad (34)$$

## Case II  Over-damped condition, ζ>1

For this condition, the parameter ω is defined as

$$\omega = \sqrt{\alpha^2 - \omega_o^2} = \omega_o\sqrt{\zeta^2 - 1} \quad (35)$$

Equations (9) and (10) become, respectively

$$e = E - (E - RI)(\cosh\omega t - \frac{\alpha}{\omega}\sinh\omega t)\epsilon^{-\alpha t} + \frac{I}{C\omega}\sinh\omega t\cdot\epsilon^{-\alpha t} \quad (36)$$

$$de/dt = (E - RI)(2\alpha\cosh\omega t - \frac{\omega^2 + \alpha^2}{\omega}\sinh\omega t)\epsilon^{-\alpha t} + \frac{I}{C}(\cosh\omega t - \frac{\alpha}{\omega}\sinh\omega t)\epsilon^{-\alpha t} \quad (37)$$

If condition (16) holds, the peak voltage occurs at a time $t_1$ obtained by setting (37) equal to zero and solving

$$\tanh\omega t_1 = \frac{(E-RI)\,2\alpha + \frac{I}{C}}{(E-RI)\frac{\omega^2 + \alpha^2}{\omega} + \frac{I\alpha}{C\omega}} \quad (38)$$

$$= \frac{-(2\zeta - 4\zeta^2\chi + \chi)\sqrt{\zeta^2 - 1}}{1 - 3\zeta\chi - 2\zeta^2 + 4\zeta^3\chi} \quad (39)$$

$$= g(\zeta,\chi) \text{ (definition of function)} \quad (40)$$

$$t_1 = \frac{\tanh^{-1} g(\zeta,\chi)}{\omega_o\sqrt{\zeta^2 - 1}} \quad (41)$$

$$= \frac{\frac{1}{2}\log\left[\frac{1 + g(\zeta,\chi)}{1 - g(\zeta,\chi)}\right]}{\omega_o\sqrt{\zeta^2 - 1}} \text{ if} \quad (42)$$

$$|g(\zeta,\chi)| < 1$$

Substituting $t_1$ into (36), the same expression as (22) for the peak recovery voltage $E_1$ is obtained.

The normalized peak voltage as a function of ζ and χ becomes

$$q(\zeta,\chi) = \frac{E_1}{E} = 1 + \exp\left\{-\frac{\zeta}{\sqrt{\zeta^2 - 1}}\cdot\tanh^{-1} g(\zeta,\chi)\right\}\sqrt{1 - 2\zeta\chi + \chi^2} \quad (43)$$

The average rate of rise of voltage to this peak value is

$$\left(\frac{dv}{dt}\right)_{avg} = \frac{E_1}{t_1} = E\omega_o \frac{q(\zeta,\chi)\sqrt{\zeta^2 - 1}}{\tanh^{-1} g(\zeta,\chi)} \quad (44)$$

$$= \frac{E^2}{LI} \frac{\chi q(\zeta,\chi)\sqrt{\zeta^2 - 1}}{\tanh^{-1} g(\zeta,\chi)} \quad (45)$$

## Case III. Critically damped condition, ζ = 1

For this condition, $\alpha = \omega_o$ \quad (46)

$$\text{and}\left(\frac{e}{E}\right)_o = \frac{RI}{E} = 2\chi \qquad (47)$$

The inverse transform of (2) yields

$$e = E - (E - RI)(1 - \alpha t)\epsilon^{-\alpha t}$$
$$+ \frac{1}{2} RI\, \alpha t\, \epsilon^{-\alpha t} \qquad (48)$$

Differentiating (48)

$$de/dt = \left[E(2 - \alpha t) + \frac{1}{2} RI(\alpha t - 3)\right] \cdot$$
$$\alpha\, \epsilon^{-\alpha t} \qquad (49)$$

If condition (15) is satisfied ($\chi < 2/3$), the peak voltage is attained at a time $t_1$ which can be found by setting (49) equal to zero, yielding

$$\alpha t_1 = \frac{2 - \frac{3}{2}\frac{RI}{E}}{1 - \frac{RI}{2E}} \qquad (50)$$

$$t_1 = \frac{1}{\omega_o} \cdot \frac{2 - 3\chi}{1 - \chi} \qquad (51)$$



Fig. 3   Peak Voltage as a Function of Damping and Initial Current

Substituting from (50) into (48), the normalized peak recovery voltage is

$$\frac{E_1}{E} = 1 + (1 - \chi) \exp\left(-\frac{2 - 3\chi}{1 - \chi}\right) \qquad (52)$$

The average rate of rise of voltage to this peak is

$$\left(\frac{dv}{dt}\right)_{avg} = \frac{E_1}{t_1} = E\omega_o\left(\frac{1 - \chi}{2 - 3\chi}\right)\left[1 + (1 - \chi)\cdot\right.$$
$$\left. \exp\left(-\frac{2 - 3\chi}{1 - \chi}\right)\right] \qquad (53)$$

$$= \frac{E^2}{LI} \chi \left(\frac{1 - \chi}{2 - 3\chi}\right)\left[1 + (1 - \chi)\exp\right.$$
$$\left.\left(-\frac{2 - 3\chi}{1 - \chi}\right)\right] \qquad (54)$$

Snubber Circuit Design for Minimum Voltage Spike

The normalized peak voltage $E_1/E$ computed from (23), (43) or (52) is plotted in Fig. 3 as a function of the damping factor $\zeta$, with the initial current factor $\chi$ as a parameter. These curves are similar to those obtained by Von Zastrow and Galloway from numerical solution of the differential equations of the circuit by computer methods [1]. For a given value $\chi_o$ of the parameter $\chi$, there is a particular value $\zeta_o$ of the parameter $\zeta$ which will minimize the peak voltage ratio $(E_1/E)_o$. Selecting $\zeta = \zeta_o$ represents an optimum snubber design for minimizing the voltage spike with a given capacitance (assuming the inductance L and peak recovery current I are pre-determined), or for minimizing the capacitance required to limit the spike to a specified value. Thus, if $(E_1/E)_o$ is the allowable voltage ratio, the optimum snubber design may be obtained from Fig. 4.

$$\chi_o = \text{function of } (E_1/E)_o \qquad (55)$$

$$\zeta_o = \text{function of } (E_1/E)_o \qquad (56)$$

$$C = L\left(\frac{I}{E\,\chi_o}\right)^2 \qquad (57)$$

$$R = 2\zeta_o\sqrt{\frac{L}{C}} = 2\zeta_o\, E\chi_o/I \qquad (58)$$

The average $dv/dt$, normalized with respect to $E\omega_o$, is also shown on Fig. 4.

Note that the parameters obtained from Fig. 4 are optimum only if $dv/dt$ is of no consequence, such as may be the case for diodes and reverse voltages on thyristors. However, reverse recovery $dv/dt$ limitations are now appearing in some power device specifications.
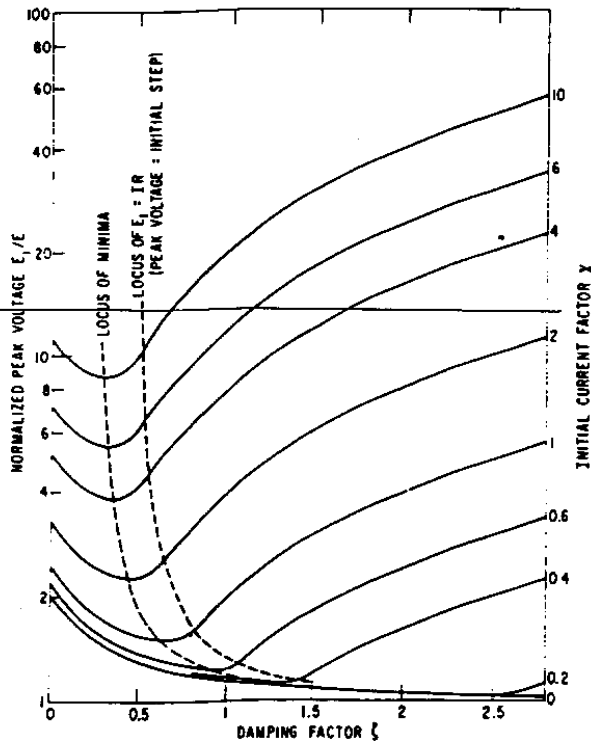
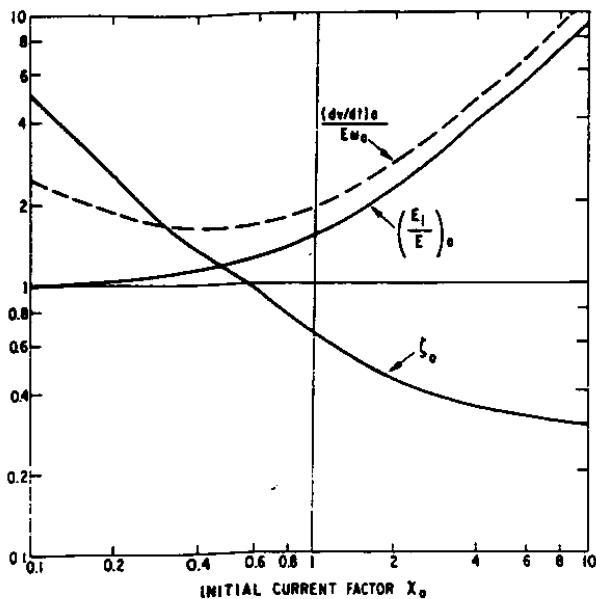Fig. 4 Optimum Snubber Design Parameters for Minimum Voltage Spike



Fig. 6 Optimum Snubber Parameters for Minimum dv/dt

## Snubber Circuit Design for Minimum dv/dt

If the recovering device has a thyristor connected inversely across it, then its reverse recovery dv/dt appears in the forward direction with respect to that thyristor, and becomes critically important. For example, many cycloconverters and reversing d-c motor drives use inverse-parallel
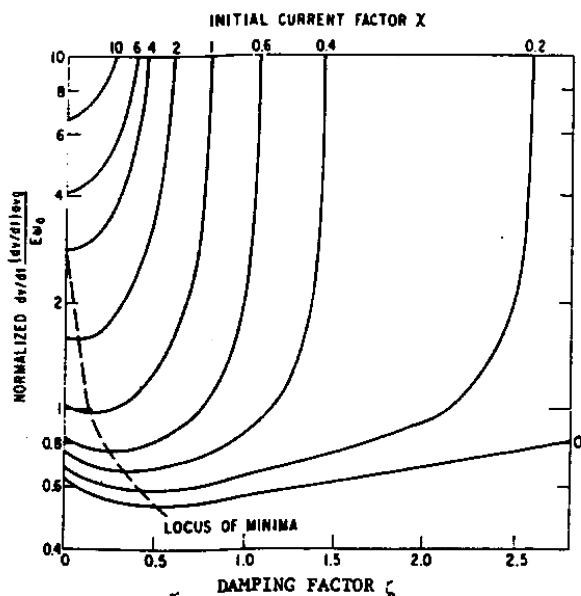


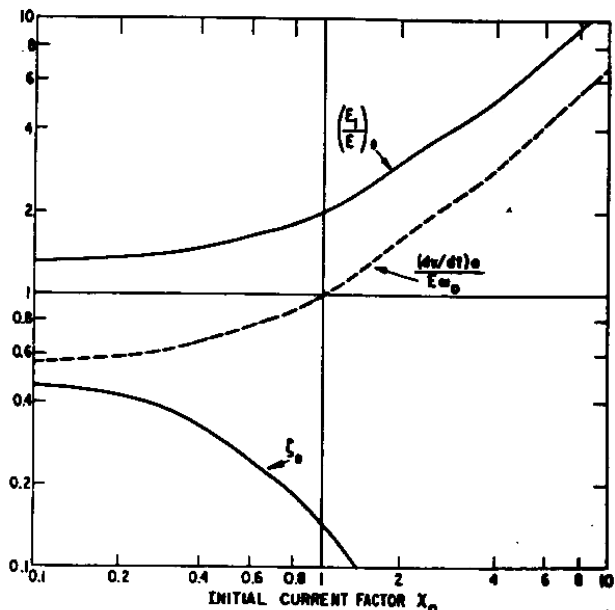Fig. 5 Average dv/dt as a Function of Damping and Initial Current

pairs of thyristors. In some inverters, feedback rectifiers are connected directly across the thyristors. Here, the reverse recovery of the rectifier occurs just after commutation of the thyristor, a time when dv/dt is most critical. If the device itself is a bidirectional thyristor (of the triode or diode type), its recovery dv/dt must again be limited.

In discussing dv/dt, the problem of definition arises for all cases except a linear rise at constant slope. For example, the initial slope or the maximum instantaneous slope may be used. Sometimes an exponential rise is assumed for defining or testing purposes. In the ideal case analyzed in the previous sections, where the recovery current is assumed to "snap" off, the initial dv/dt is theoretically infinite. Therefore, the dv/dt is here defined as the average slope to the voltage peak. The circuit designer and device rating engineer should co-operate in determining that the actual shape of the transient is consistent with preventing the thyristor from self-triggering, which is the main purpose of limiting dv/dt.

The normalized average dv/dt computed from (24), (44) or (53) is plotted in Fig. 5 as a function of the damping factor $\zeta$, with the initial current factor $\chi$ as a parameter. It is seen that for a given value $\chi_o$ of the parameter $\chi$, there is a particular choice of damping ($\zeta_o$) which will minimize the average dv/dt at some value $(dv/dt)_o$. These optimum design parameters are shown in Fig. 6, together with the corresponding peak voltage ratio $(E_1/E)_o$, from which a snubber may be designed to give a specified dv/dt using minimum capacitance. Note that minimum dv/dt is obtained with less damping than required to minimize the voltage spike.

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## Compromise Design of Snubber Circuit

In most applications, the peak recovery voltage and dv/dt across a thyristor are both important, and a damping factor selected to compromise between minimum voltage spike and minimum dv/dt is recommended. The set of parameters for that amount of damping which will minimize the product of $E_1$ and $(dv/dt)_{avg}$ for a given capacitance (still assuming that the inductance L and peak recovery current I are pre-determined by other considerations) are presented in Fig. 7. The product $E_1(dv/dt)$ was chosen as a convenient function for a computer minimization program.

The design procedure is as follows:

1. Select a tolerable peak voltage $E_1$ and calculate $(E_1/E)_o$.

2. From Fig. 7, read the corresponding values of $x_o$, $\zeta_o$ and $(dv/dt)_o/E\omega_o$.

3. Calculate C, R, $\omega_o$ and $(dv/dt)_o$ using (57), (58) and (3).

If the resulting value of dv/dt is larger than permissible, a larger capacitance is required and the parameter $x_o$ should be selected on the basis of dv/dt limitation. To aid this selection, the optimum dv/dt normalized with respect to the pre-determined factor $E^2/LI$ is plotted in Fig. 8. The procedure is as follows:

1. For the allowable $(dv/dt)_o$, calculate $(dv/dt)_o \cdot LI/E^2$.
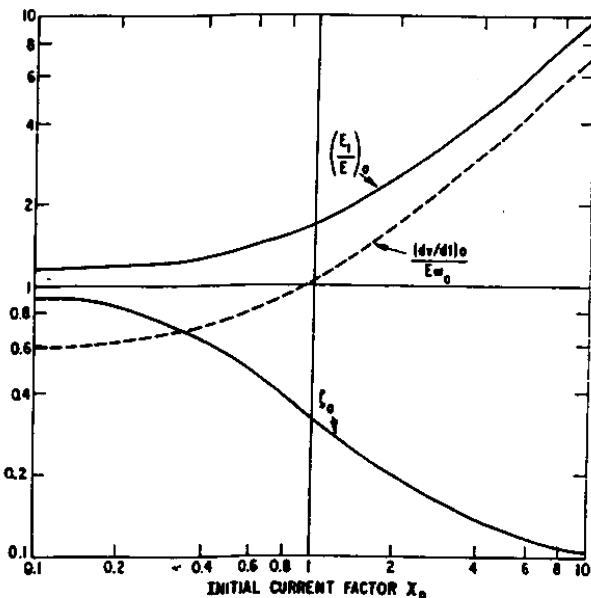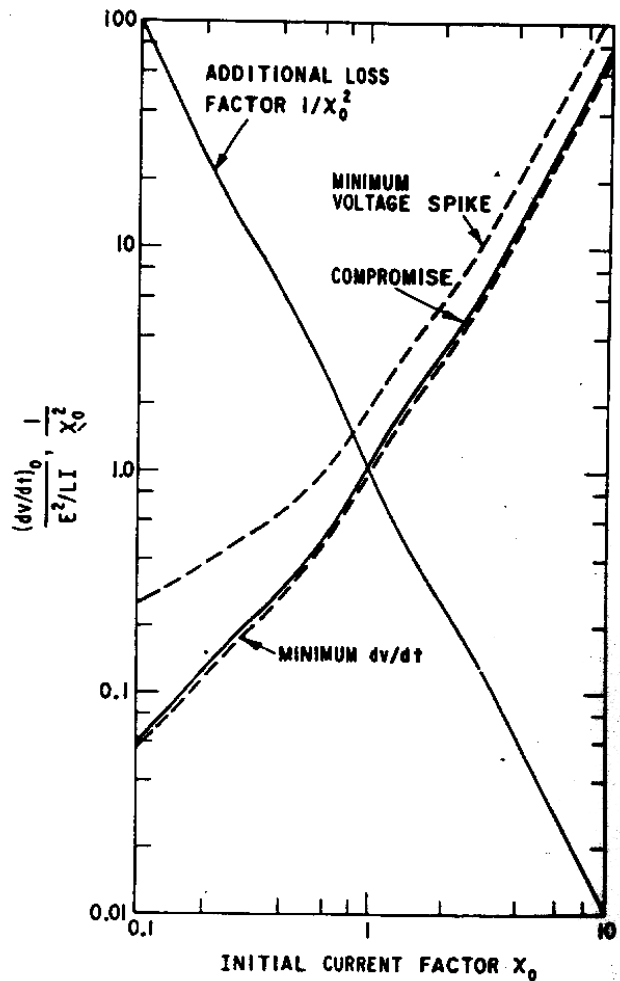
Fig. 7 Optimum Snubber Parameters for Compromise Design

Fig. 8 Optimum dv/dt Factors and Additional Loss Factor

2. From Fig. 8, read the corresponding value of $x_o$, using the "compromise" curve.

3. Enter Fig. 7 with this value $x_o$ and read $\zeta_o$ and $(E_1/E)_o$.

4. Calculate C and R using (57) and (58), and use the nearest standard values.

This compromise design is recommended for most practical applications. In rare cases where the limitations on peak voltage or dv/dt are abnormally stringent, such as to accentuate the importance of one over the other, then Fig. 4 or Fig. 6 and the corresponding curves on Fig. 8 may be used. However, note that there is little improvement in the critical parameter over that given by the compromise design for the same value of $x_o$.

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A plot of a typical recovery transient with a snubber designed for "compromise" damping is shown in Fig. 9, for $\chi = 0.6$, $\zeta = 0.475$. The thyristor and capacitor voltages are shown; the voltage across the resistor (proportional to current) is the difference between the two curves. The slope of the dashed line in Fig. 9 is the normalized average dv/dt.

For the ideal case where the recovery current is negligible, $\chi \rightarrow 0$ and the asymptotes of the "compromise" curves yield

$$\left. \begin{array}{l} \zeta = 0.964 \\ \\ E_1/E = 1.142 \\ \\ (dv/dt)_{avg}/E\omega_o = 0.564 \end{array} \right\} \qquad (59)$$

## Snubber Losses at Time of Recovery

First, a general expression for the losses in a series L-C-R circuit fed from a d-c source will be obtained in terms of the initial and final state variables. Then, the snubber loss during the recovery transient is obtained as a special case.

Suppose, in the circuit of Fig. 1, that the capacitor voltage changes from $V_1$ to $V_2$ and the current changes from $I_1$ to $I_2$ in a time interval from $t_1$ to $t_2$. If v is the instantaneous capacitor voltage and i the instantaneous current, they are related by

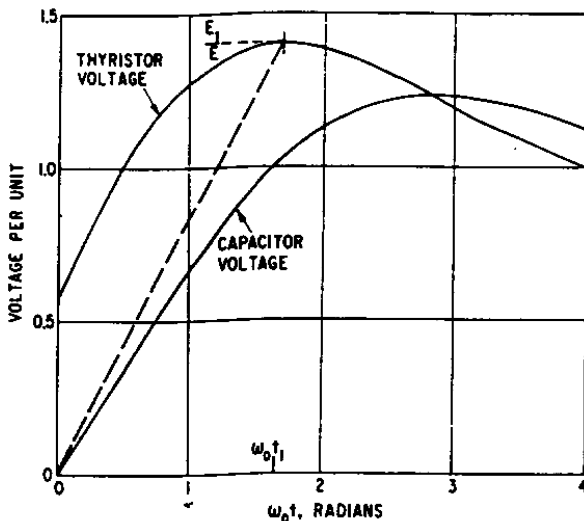$$i \, dt = C \, dv \qquad (60)$$

Fig. 9 Typical Recovery Voltage Transient
$\chi = 0.6$, $\zeta = 0.475$

The loss W in resistor R may be determined from the energy balance requirement:

Loss = Energy from source - Increase in Energy Stored in Capacitor

- Increase in Energy Stored in Inductor

$$\int_{t_1}^{t_2} i^2 R \, dt = E \int_{t_1}^{t_2} i \, dt - C \int_{V_1}^{V_2} v \, dv - L \int_{I_1}^{I_2} i \, di \qquad (61)$$

$$W = EC \, (V_2 - V_1) - \frac{1}{2}C \, (v_2^2 - v_1^2) - \frac{1}{2}L \, (I_2^2 - I_1^2) \qquad (62)$$

$$= C \, (V_2 - V_1)\left(E - \frac{V_2 + V_1}{2}\right) - \frac{1}{2}L \, (I_2^2 - I_1^2) \qquad (63)$$

This is the desired general expression for loss. For the snubber circuit, $V_1 = 0$, $V_2 = E$, $I_1 = I$, $I_2 = 0$

$$W = \frac{1}{2} CE^2 + \frac{1}{2} LI^2 \qquad (64)$$

$$= \frac{1}{2} LI^2 \left(1 + \frac{1}{\chi^2}\right) \qquad (65)$$

Note that all of the energy trapped in the inductance at the time of recovery is inevitably dissipated. The factor $1/\chi^2$, plotted in Fig. 8, represents the per unit additioanl loss, which is the penalty paid for limiting dv/dt and the voltage spike. Besides the loss at the time of recovery, the snubber will dissipate energy equal to 1/2C $(\Delta E)^2$ any time a step voltage change $(\Delta E)$ occurs in the voltage waveform across the device. The losses due to the smoothly-varying portions of the waveform, such as a sinusoidal supply voltage, are generally negligible in comparison with the step losses.

## Snubber Loss and Thyristor Dissipation

### at Time of Turn-on

In particular, when a thyristor turns on from a voltage E, an energy loss 1/2 $CE^2$ will occur. Because of the finite voltage fall time of the thyristor, some of this energy will be dissipated in the thyristor instead of the damping resistor, and the capacitor discharge increases the initial di/dt in the thyristor. An estimate of the fraction of the snubber discharge loss that is absorbed by the thyristor can be derived if some simplifying assumption is made regarding the thyristor voltage fall characteristic. For example, suppose that the thyristor voltage falls exponentially with a time constant $\tau$ and is independent of the current, then

$$e = E \, \epsilon^{-t/\tau} \qquad (66)$$

Note that this exercise is not intended to imply
that any actual thyristor has such a characteris-
tic, but only to provide a simple order-of-magni-
tude loss estimate if the observed fall interval
can be approximately fit to such a curve.

The discharge current i of a snubber having
a time constant $\tau_s = RC$ is given by

$$i = \frac{E}{R} \quad \frac{\tau_s}{\tau_s - \tau} \left( \epsilon^{-t/\tau_s} - \epsilon^{-t/\tau} \right) \quad (67)$$

The energy $W_t$ absorbed by the thyristor is then

$$W_t = \int_0^\infty ei \, dt = \frac{E^2}{2R} \frac{\tau_s \tau}{\tau_s + \tau} \quad (68)$$

which is, as a fraction of the total loss

$$\frac{W_t}{\frac{1}{2}CE^2} = \frac{\tau}{\tau_s + \tau} \quad (69)$$

This result simply states that the loss is divided
between the thyristor and its snubber in propor-
tion to their respective time constants.

If the rise of load current $i_L$ in a parallel
path through the same thyristor is limited by an
inductance L and driven by the voltage (E - e),
where the thyristor voltage e is the same assumed
exponential fall (66), then

$$\frac{di_L}{dt} = \frac{E - e}{L} = \frac{E}{L} \left( 1 - \epsilon^{-t/\tau} \right) \quad (70)$$

$$i_L = \frac{E}{L} \left[ t - \tau \left( 1 - \epsilon^{-t/\tau} \right) \right] \quad (71)$$

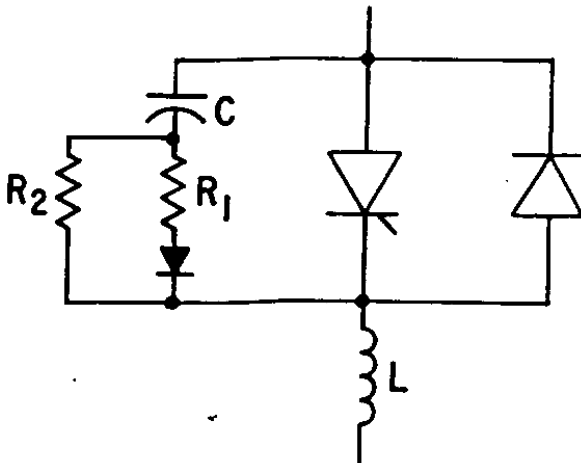The thyristor dissipation produced by this load
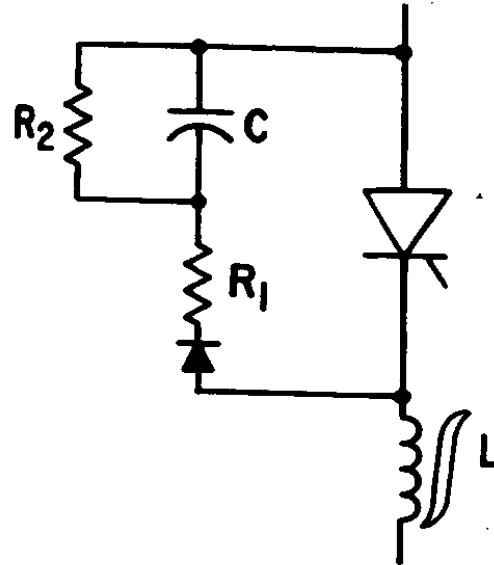current rise is

Fig. 10 Forward Polarized Snubber

Fig. 11 Reverse Polarized Snubber

$$W_L = \int_0^\infty ei_L \, dt = \frac{E^2}{2L} \tau^2 \quad (72)$$

In practice, the rise of load current will not
continue indefinitely, but will terminate at
some level $I_L$. However, equation (72) for the
switching loss will be approximately true if the
time to reach the current $I_L$ is several times
greater than the time constant $\tau$. If the snubber
time constant is much greater than the thyristor
fall time ($\tau_s \gg \tau$), the ratio of the two contri-
butions to the thyristor switching loss simplifies
to

$$\frac{W_t}{W_L} \approx \frac{L/R}{\tau} \quad (73)$$

When the snubber discharge results in ex-
cessive thyristor switching loss $W_t$, a polarized
snubber arrangement should be considered. Where
the primary function of the snubber is to limit
the forward dv/dt applied to a thyristor at the
time of recovery of an inverse feedback rectifier,
the scheme shown in Fig. 10 is often used. The
resistor $R_1$ is the damping resistance effective
during forward dv/dt, while $R_2$ is a much larger
resistance to limit the snubber discharge current
when the thyristor is fired.

When forward voltage is reapplied to a thy-
ristor as a ramp of relatively low dv/dt, the
prime purpose of the snubber is to limit the re-
verse voltage spike. Here, the arrangement of
Fig. 11 can be used to advantage. Damping resis-
tance $R_1$ is effective during reverse recovery,
while resistance $R_2$ of higher value discharges
the snubber capacitor C during the period of
forward voltage before the thyristor is fired
again.

Note that polarized snubbers do not reduce
the circuit losses, but only prevent the losses
from being dissipated in the thyristor. For
example, a reverse polarized snubber prevents
positive charge from being put on the snubber
capacitor during the low-loss ramp dv/dt, but the
blocked reverse charge is dissipated in the dis-
charge resistor.

When a pair of thyristors are connected in
inverse parallel, as in a cycloconverter, the
snubber must be effective during recovery of
either polarity. Therefore, a polarizing arrange-
ment does not appear to be practical, as indicated
in Fig. 12. However, it may be possible to reduce
the snubber size by employing non-linear reactors
which are unsaturated and have a high value of in-
ductance at the time of recovery when the current
is close to zero. Such reactors, shown in Figs.
11 and 12, also reduce the initial di/dt after
turn-on [2]. Experience has shown that non-linear
reactors cannot be advantageously employed in cir-
cuit arrangements of the type shown in Fig. 10.

## Conclusions

A procedure for selecting the optimum capaci-
tance and damping resistance for a simple snubber
used to limit the recovery transient of power
rectifiers or thyristors has been presented. In
some circuits, the recovery of one device produces
steps of voltage not only across itself but across
other devices in the circuit as well. These other
devices often have snubbers which contribute to
suppression of the transient, and the size of the
snubber provided for each device may be reduced.
The circuit action during the recovery transient
can often, but not always, be represented by an
equivalent circuit of the simple form in Fig. 1
[3, 4]. Sometimes, a snubber designed to suppress
one transient will not be optimum for suppressing
another transient occurring at a different time in
the cycle and a compromise must be made. More com-
plex snubber arrangements may also be used, such
as the bridge circuit [4].

The energy of the device recovery current
trapped in the commutating inductance must be
dissipated in the snubber, and the charging of the
snubber capacitor by a voltage step causes addi-
tional losses as the price of its limiting func-
tion. In the typical transient shown in Fig. 9,
the additional loss at the time of recovery amounts
to 2.78 times the energy $1/2\ LI^2$. When the thy-
ristor is subsequently fired, the capacitor energy
is dissipated, and a considerable fraction of it
may be absorbed by the thyristor if the snubber is
not polarized. If the turn-on voltage is the same
as the commutating voltage, the discharge loss is
also 2.78 times the trapped recovery energy. Thus,
the need to dissipate recovery energy requires a
total additional dissipation of about six times
that recovery energy. For high frequency opera-
tion, the need for devices having a small recovery
current and high dv/dt capability as well as high
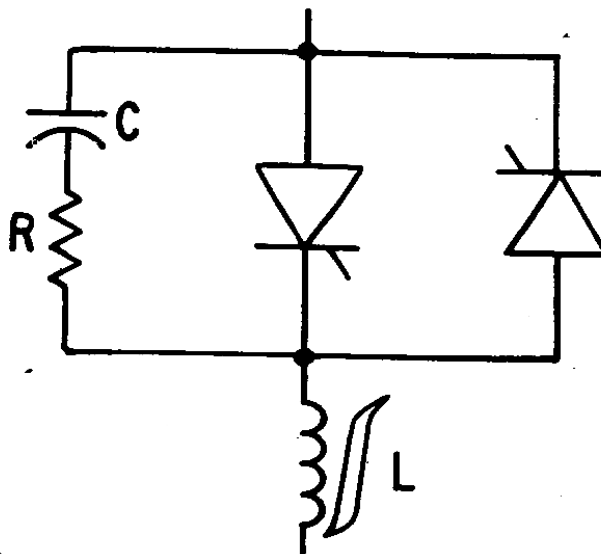di/dt capability becomes apparent.



Fig. 12 Unpolarized Snubber

## References

1. E. E. VonZastrow and J. H. Galloway, "Commu-
tation Behaviour of Diffused High Current
Rectifier Diodes", IEEE International Conven-
tion Record, 1964, Part 4, p. 106. (Also
available as GE-SPD Application Note 200.42,
June 1965.)

2. D. A. Paice and P. Wood, "Nonlinear Reactors
as Protective Elements for Thyristor Circuits,"
IEEE Trans. on Magnetics, Vol. MAG-3, No. 3,
Sept. 1967, pp. 228-232.

3. J. B. Rice and L. E. Nickels, "Commutation
dv/dt Effects in Thyristor Three-Phase Bridge
Converters," IEEE Trans. on Industry and
General Applications," Vol. IGA-4, No. 6,
Nov./Dec 1968, pp. 665-672.

4. G. Thiele, "Richtlinien für die Bemessung der
Trägerspeichereffekt-Beschaltung von Thyris-
toren" (Guiding Principles for the Design of
Carrier-Storage Effect Connections for Thy-
ristors), ETZ-A Vol. 90, No. 14, 1969, pp.
347-352.