

Estimation of Turn-off Losses In a Thyristor Due to Reverse Recovery

Application Note

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Introduction:

The total power losses in a thyristor are comprised of off-state losses, switching losses and conduction losses. The off-state losses are the steady state losses as a result of blocking voltage and current (leakage current). The switching losses are the dynamic losses encountered during the turn-on and the reverse recovery phases of the thyristor. The conduction losses are the steady state on-state losses during the conduction phase of the thyristor. In the majority of the phase control thyristor applications the conduction losses are the dominant power losses compared to others. Therefore it is often sufficient to design thermal circuit using just the conduction losses with some safety margin. To help towards this process Dynex i^2 phase control thyristor datasheets give charts of power dissipation under the commonly encountered waveforms such as sine wave and the rectangular wave for different conduction angles.

The switching power losses are the function of the repetition frequency and the commutating di/dt . Therefore these losses become significant at higher frequencies and for high di/dt . For high voltage applications the contribution made by the reverse recovery losses can no longer be ignored. The reverse recovery energy is given by:

$$E_{rec} = \int I_{rec}(t) \times V_R(t) dt \quad (1)$$

To calculate the energy loss as per equation (1), detailed knowledge of the reverse recovery current and voltage waveforms is

required. This is usually acquired through actual measurements in the real circuit. However for initial design purposes and dimensioning of the device, a quick method of estimating the recovery losses is desirable. In this Application Note a method of estimating power losses due to reverse recovery is outlined.

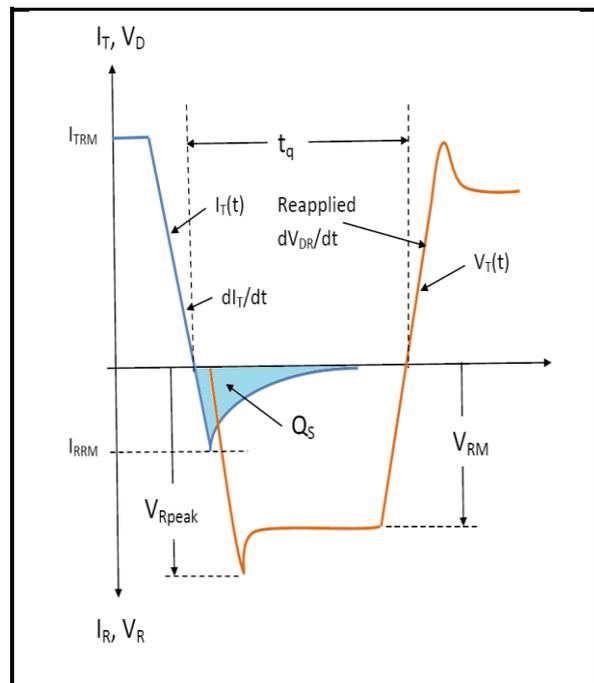


Fig. 1 Thyristor Turn-off waveforms

Approximation of reverse recovery waveforms:

Fig. 1 shows the current and voltage waveforms observed during the turn-off phase of a thyristor. The charge stored during the conduction phase is extracted as reverse recovery current when a thyristor undergoes turn-off. The reverse recovery phase is

characterised by the peak reverse recovery current I_{RR} and the recovered charge Q_S . Q_S is given by the integral of the reverse recovery current.

$$Q_S = \int I_{rec}(t) dt \quad (2)$$

This is the shaded area in Fig. 1. For practical reason the datasheet value of Q_S is integrated for 150µs by which time the reverse recovery current is virtually zero.

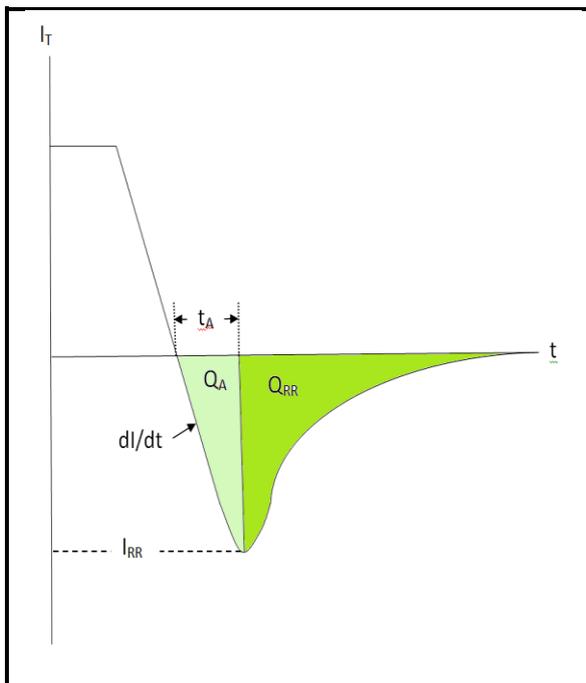


Fig. 2 Triangular Approximation

In Fig. 2 the total charge Q_S is divided into two regions, Q_A and Q_{RR} respectively; where

$$Q_A = \int_0^{t_A} I_{rec}(t) dt \quad (3)$$

$$Q_{RR} = \int_{t_A}^{\infty} I_{rec}(t) dt \quad (4)$$

The reverse voltage during the time interval t_A is negligible (Fig. 1) and hence energy contribution during the period t_A can be approximated to zero. Then from (1 and 4),

$$E_{rec} \approx V_R \int_{t_A}^{\infty} I_{rec}(t) dt \quad (5)$$

where V_R is assumed to be quasi constant and equal to applied peak reverse voltage V_{Rpeak} .

And from (5),

$$E_{rec} \approx 0.5 \times V_{Rpeak} \times Q_{RR} \quad (6)$$

Also,

$$E_{rec} \approx 0.5 \times V_{Rpeak} \times (Q_S - Q_A) \quad (7)$$

The charge Q_A can be approximated by the area of a triangle formed by I_{RR} and t_A . Thus

$$Q_A = 0.5 \times I_{RR} \times t_A \quad (8)$$

But

$$t_A = I_{RR} / di/dt \quad (9)$$

Thus

$$Q_A = \frac{0.5 \times I_{RR}^2}{di/dt} \quad (10)$$

Substituting in (7) we get,

$$E_{rec} \approx 0.5 \times V_{Rpeak} \times \left(Q_S - \frac{0.5 \times I_{RR}^2}{\frac{di}{dt}} \right) \quad (11)$$

Worked example:

For illustration purpose, thyristor part number DCR3030V42 is chosen and the charts of stored charge and reverse recovery current from the datasheets are reproduced in the Fig. 3 and Fig. 4 respectively.

The calculation begins with known parameters of the circuit the V_{RM} (line voltage), V_{Rpeak} (controlled by the snubber circuit) and the di/dt . The di/dt of the turn-off current is usually controlled by the commutation inductance L_C .

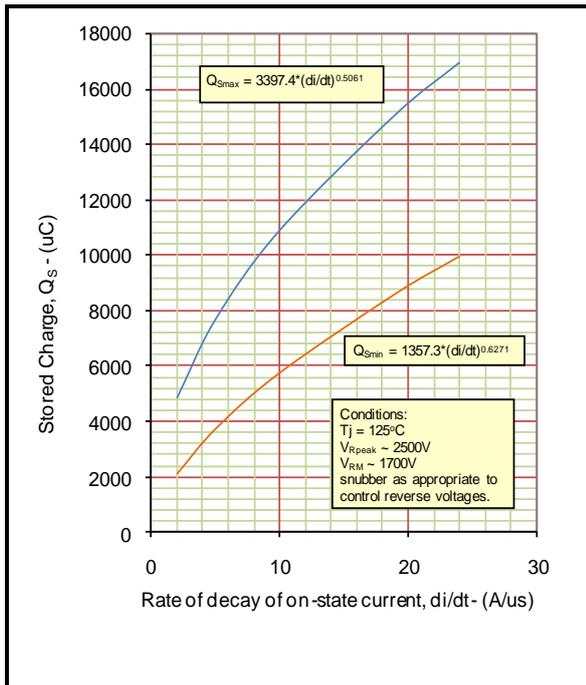


Fig. 3 Stored Charge

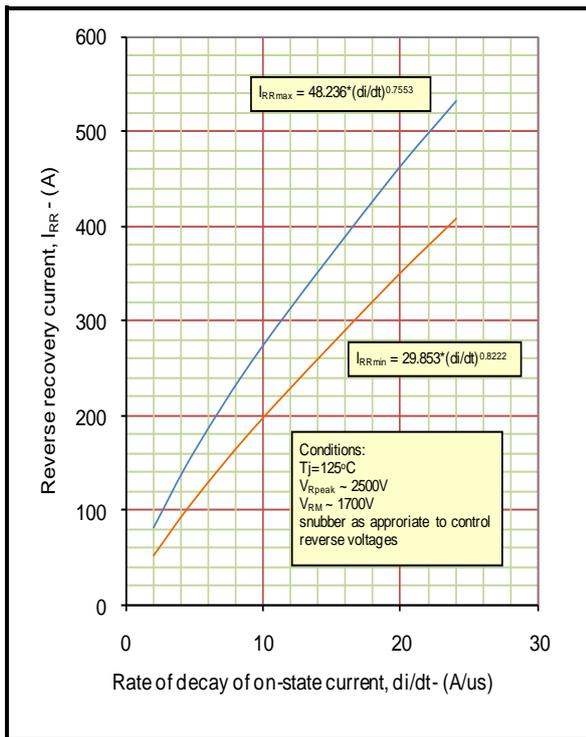


Fig. 4 Reverse Recovery Current

Thus

$$di/dt = V_{RM}/L_c$$

If we assume $di/dt = 10A/us$, the value of Q_s is given by using the equation on the chart of Fig. 3; $Q_{smax} = 3397.4 \times (10)^{0.5061} = 10895\mu C$

and $Q_{smin} = 1357.3 \times (10)^{0.6271} = 5751\mu C$. Similarly from chart of Fig. 4 the $I_{RRmax} = 275A$ and $I_{RRmin} = 198A$. V_{Rpeak} is 2500V.

Using the equation (11),

$$E_{rec(max)} = 8.89J \text{ and } E_{rec(min)} = 4.74J \text{ per pulse.}$$

If the repetition frequency is say 50Hz, then the power losses are:

$$P_{rec(max)} = 8.89 \times 50 = 444.5W \text{ and}$$

$$P_{rec(min)} = 4.74 \times 50 = 237W.$$

It should be noted that the minimum recovery losses correspond to the maximum conduction losses and vice a versa. Ideally both the conditions should be calculated and the worst case value should be used to design the thermal circuit (heat sink etc). Using both the maximum conduction losses and maximum recovery losses will lead to over dimensioning of the heatsink.

Measurement Method:

In this method the reverse recovery energy is determined by the measurement of the reverse recovery current and voltage using stored charge test equipment. The thyristor part tested was DCR2400B85. Fig.5 shows the oscillogram of the measured waveforms.



Fig.5 Reverse recovery waveforms

The test conditions are:

- $T_j = 125^\circ\text{C}$
- $V_{Rpeak} = 3030\text{V}$
- Snubber setting: 14Ω and $12\mu\text{F}$

Test equipment readings:

- $Q_s = 15610\mu\text{C}$ integrated over $500\mu\text{s}$
- $I_{rr} = 225.1\text{A}$
- $di/dt = 5.5\text{ A}/\mu\text{s}$

Fig. 6 shows the digitised reverse recovery current and voltage waveforms plotted in an Excel chart. The Excel spreadsheet is used to multiply the digitised voltage and current waveforms to obtain the instantaneous power waveform as shown in Fig.7. Finally integrating this power waveform gives the energy per pulse. Again numerical integration was performed within the spreadsheet using the trapezium rule. The result of this integration gave the measured value of the reverse recovery energy:

$$E_{meas} = 17.8\text{ J.}$$

Using the approximation method (Eqn. 11) for the test results thus:

$$E_{rec} = 0.5 \times 3030 \times (15610 - (0.5 \times (225.1)^2 / 5.5)) = 16.7\text{ J.}$$

The approximation result is within 10% of the measured value.

Using the datasheet curves for DCR2400B85, the maximum and minimum values of recovery energy per pulse are 21.7 J and 15.9 J respectively.

Conclusion:

A method for estimating reverse recovery losses in a thyristor using datasheet curves is presented and verified with actual measurement. The approximated value lies within 10% of the measured value.

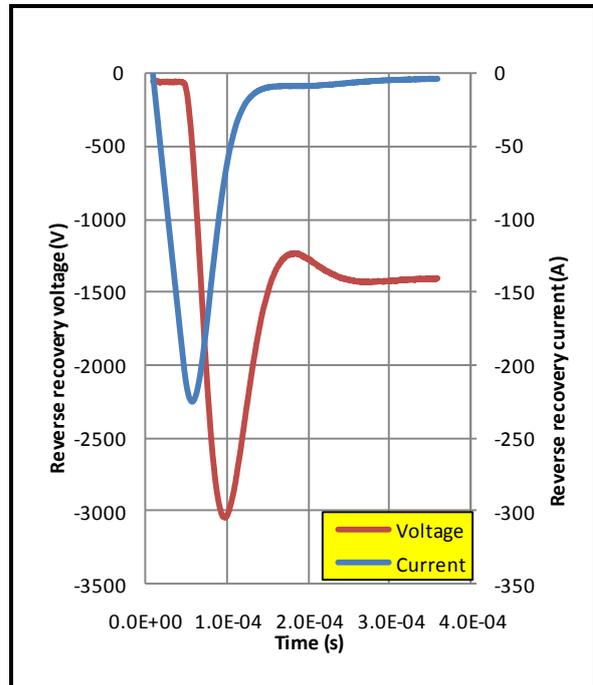


Fig. 6 Reverse recovery current and voltage

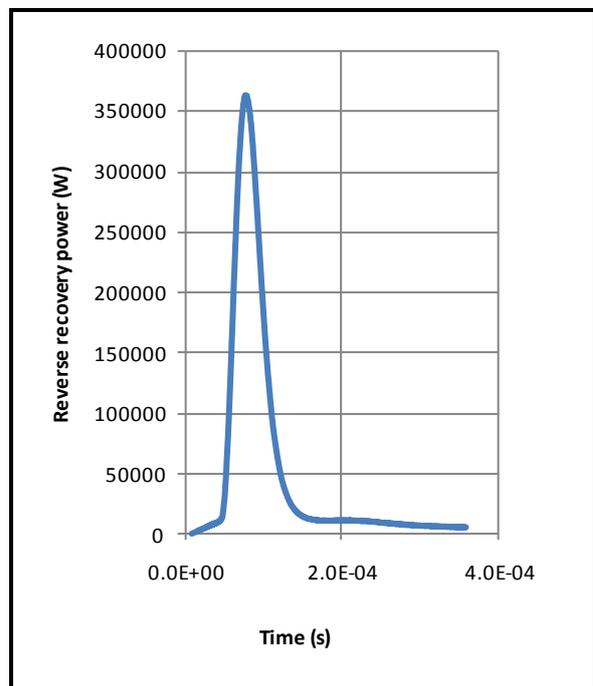


Fig. 7 Reverse recovery instantaneous power

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