Email: powersolutions@dynexsemi.com
Main switchboard: +44 (0)1522 500 500
Website: www.dynexsemi.com

AN5951
Estimation of Turn-off Losses in a Thyristor due to Reverse Recovery
Application Note

Replaces AN5951-3
AN5951-4 November 2022 (LN42257)

Introduction:

The total power losses in a thyristor are comprised of off-state losses, switching losses and conduction losses. Off-state losses are the steady state losses as a result of blocking voltage and current (leakage current). Switching losses are the dynamic losses encountered during the turn-on and reverse recovery phases of the thyristor. Conduction losses are the steady state on-state losses during the conduction phase of the thyristor. In the majority of phase control thyristor applications, the conduction losses dominate. Therefore, it is often sufficient to design a 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 commonly encountered waveforms such as sine and rectangular waves for different conduction angles.

Switching power losses are a 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:

$$E_{rec} = \int I_{rec}(t) \times V_R\,(t)dt \qquad [1]$$

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 recovery losses is desirable. In this Application Note a method of estimating power losses due to reverse recovery is outlined.

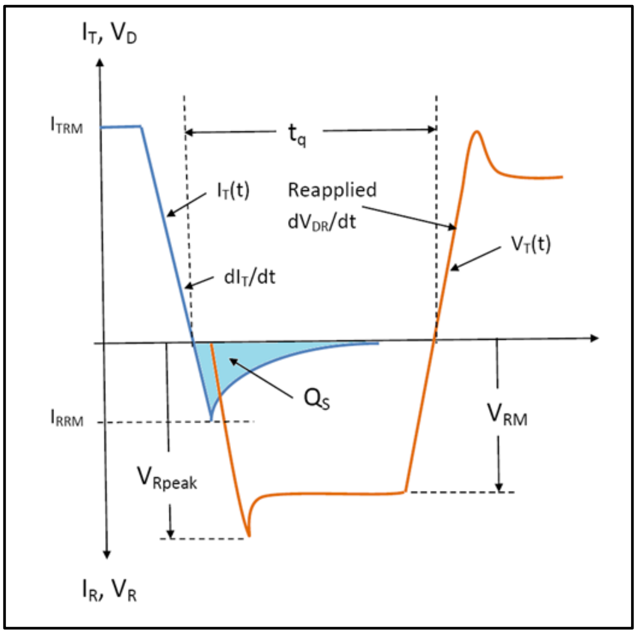


Fig. 1 Thyristor Turn-off Waveforms

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 the 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.

$$Q_S = \int I_{rec}\,(t)dt \qquad [2]$$

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

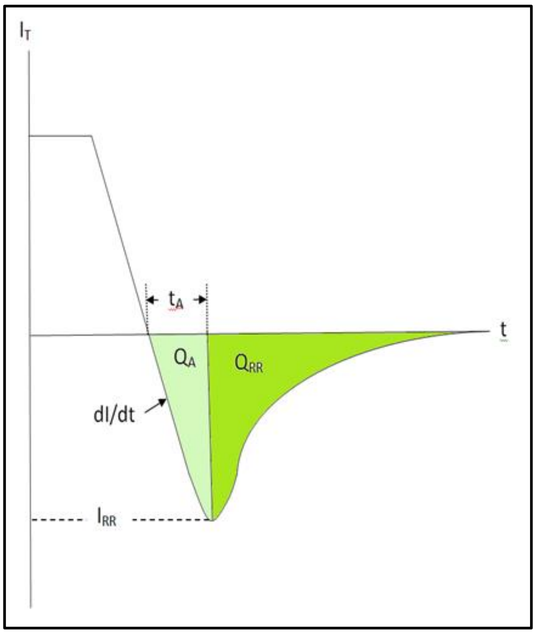


Fig. 2 Triangular Approximation

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

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

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

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]:

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

Where V_R is assumed to be quasi constant and equal to applied peak reverse voltage $V_{R(peak)}$.

And from [5]:

$$E_{rec} \approx 0.5 \times V_{Rpeak} \times Q_{RR} \qquad [6]$$

Also:

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

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

Thus:

$$Q_A = 0.5 \times I_{RR} \times t_A \qquad [8]$$

But:

$$t_A = {}^{I_{RR}}\!/_{dI/dt} \qquad [9]$$

So:

$$Q_A = \frac{0.5 \times I_{RR}^2}{dI/dt} \qquad [10]$$

Substituting in [7] we get:

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

Worked example:

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

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

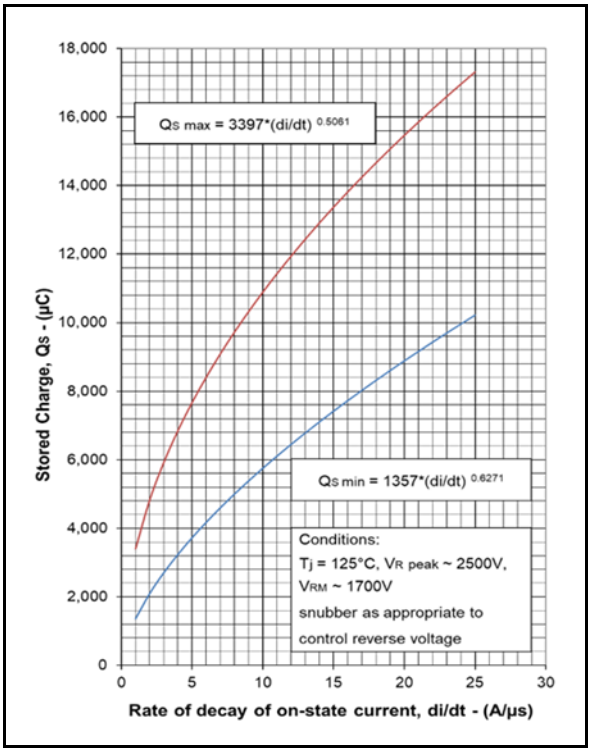


Fig. 3 Stored Charge

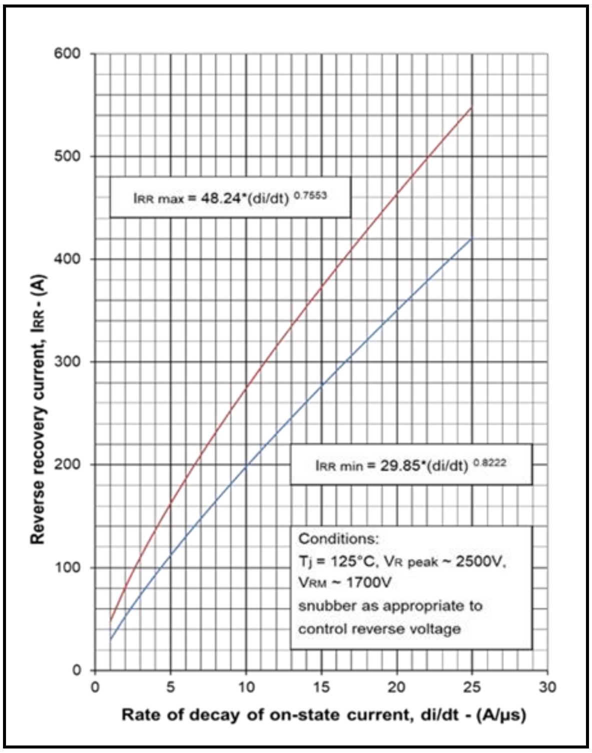


Fig. 4 Reverse Recovery Current

Thus:

$dI/dt = V_{RM}/L_C$

If we assume dI/dt = 10A/us, the value of Q_S is given by the equation on the chart in Fig. 3:

$Q_{S(max)} = 3397 \times (10)^{0.5061} = 10894\mu C$ and $Q_{S(min)} = 1357 \times (10)^{0.6271} = 5750\mu C$

Similarly, from the chart in Fig. 4:

$I_{RR(max)} = 275A$ and $I_{RR(min)} = 198A$

Note, $V_{R(peak)}$ is 2500V

Using equation [11]:

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

For a repetition frequency of 50Hz, then the power losses are:

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

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 versa. Ideally both conditions should be calculated and the worst-case value should be used to design the thermal circuit (heatsink etc.). Using both the maximum conduction losses and maximum recovery losses will lead to over-dimensioning 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.

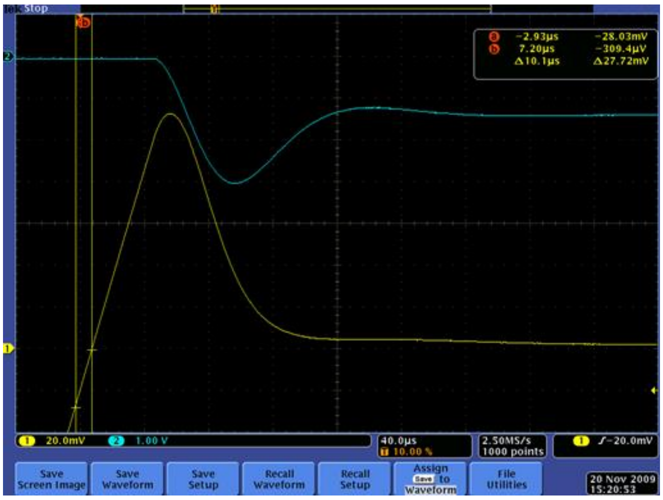


Fig.5 Reverse Recovery Waveforms

The test conditions are:

$T_j = 125°C$
$V_{R(peak)} = 3030V$
Snubber setting: 14Ω and 12µF

Test equipment readings:

Q_S = 15610µC integrated over 500µs
$I_{RR} = 225.1A$
dI/dt = 5.5A/µs

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 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 gives the measured value of the reverse recovery energy:

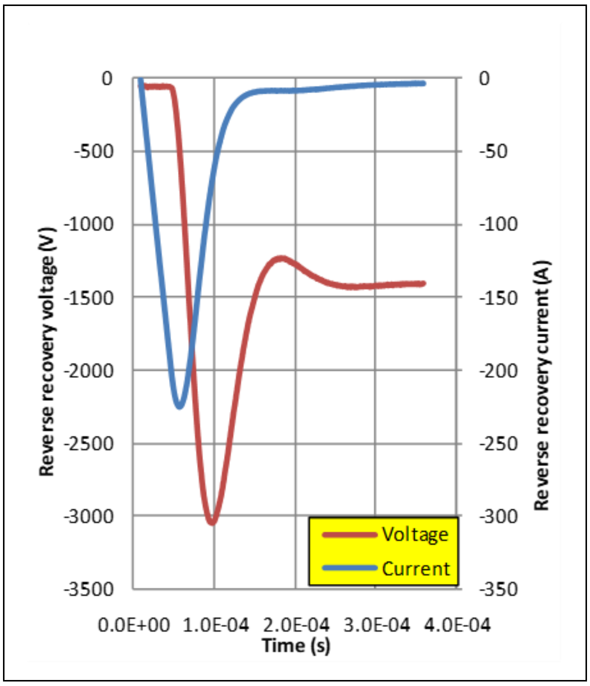
$$E_{meas} = 17.8J$$

Using the approximation method, equation [11], for the test results:

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

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 21.7J and 15.9J respectively.



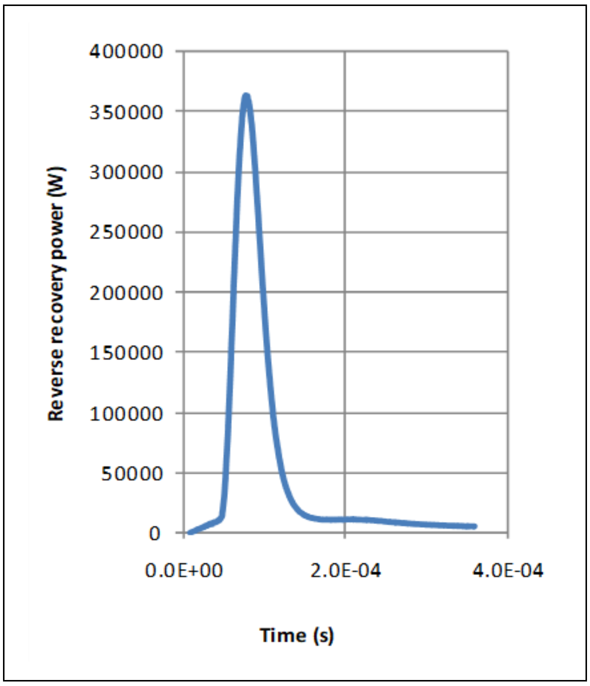


Fig. 6 Reverse Recovery Current and Voltage

Fig. 7 Reverse Recovery Instantaneous Power

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.

IMPORTANT INFORMATION:

This publication is provided for information only and not for resale.

The products and information in this publication are intended for use by appropriately trained technical personnel.

Due to the diversity of product applications, the information contained herein is provided as a general guide only and does not constitute any guarantee of suitability for use in a specific application. The user must evaluate the suitability of the product and the completeness of the product data for the application. The user is responsible for product selection and ensuring all safety and any warning requirements are met. Should additional product information be needed please contact Customer Service.

Although we have endeavoured to carefully compile the information in this publication it may contain inaccuracies or typographical errors. The information is provided without any warranty or guarantee of any kind.

This publication is an uncontrolled document and is subject to change without notice. When referring to it please ensure that it is the most up to date version and has not been superseded.

The products are not intended for use in applications where a failure or malfunction may cause loss of life, injury or damage to property. The user must ensure that appropriate safety precautions are taken to prevent or mitigate the consequences of a product failure or malfunction.

The products must not be touched when operating because there is a danger of electrocution or severe burning. Always use protective safety equipment such as appropriate shields for the product and wear safety glasses. Even when disconnected any electric charge remaining in the product must be discharged and allowed to cool before safe handling using protective gloves.

Extended exposure to conditions outside the product ratings may affect reliability leading to premature product failure. Use outside the product ratings is likely to cause permanent damage to the product. In extreme conditions, as with all semiconductors, this may include potentially hazardous rupture, a large current to flow or high voltage arcing, resulting in fire or explosion. Appropriate application design and safety precautions should always be followed to protect persons and property.

Product Status & Product Ordering:
We annotate datasheets in the top right-hand corner of the front page, to indicate product status if it is not yet fully approved for production. The annotations are as follows: -

Target Information:	This is the most tentative form of information and represents a very preliminary specification. No actual design work on the product has been started.
Preliminary Information:	The product design is complete and final characterisation for volume production is in progress. The datasheet represents the product as it is now understood but details may change.
No Annotation:	The product has been approved for production and unless otherwise notified by Dynex any product ordered will be supplied to the **current version of the data sheet prevailing at the time of our order acknowledgement.**

All products and materials are sold and services provided subject to Dynex’s conditions of sale, which are available on request.

Any brand names and product names used in this publication are trademarks, registered trademarks or trade names of their respective owners.

HEADQUARTERS OPERATIONS
DYNEX SEMICONDUCTOR LIMITED
Doddington Road, Lincoln, Lincolnshire, LN6 3LF
United Kingdom.
Phone: +44 (0) 1522 500500

Web: http://www.dynexsemi.com

CUSTOMER SERVICE
Phone: +44 (0) 1522 502753 / 502901

e-mail: powersolutions@dynexsemi.com