Switching losses for phase control and bi-directionally controlled thyristors

In thyristor applications the on-state power loss is the dominant part that can be easily calculated using the well-known equation 1.

$$P_T = V_{T0} * I_{Tav} + r_T * I_{Trms}^2 \qquad \text{E}^{\text{qn}} 1$$

It is sometimes sufficient to calculate with these losses only, when using ample margins towards the maximum allowed junction temperature. For more careful thermal dimensioning, the switching losses of the thyristor must also be taken into account, as they represent a part of the losses that, especially for high voltage devices, cannot be ignored. Since relations between device parameters and losses are too complex to be expressed in a simple formula as on-state losses, ABB has included curves showing the switching energies for a given set of conditions in the data sheets for their thyristor product range. In this application note we explain the switching processes and how the loss curves should be read.

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Contents

1 Parameter definitions

The relevant switching parameters are in this section defined and illustrated by figures where appropriate. For explanation purposes, data and diagrams associated with 5STP 26N6500 have been used, however the definitions are applicable to all phase control and bi-directionally controlled thyristors. The parameters are defined according to standard IEC 60747.
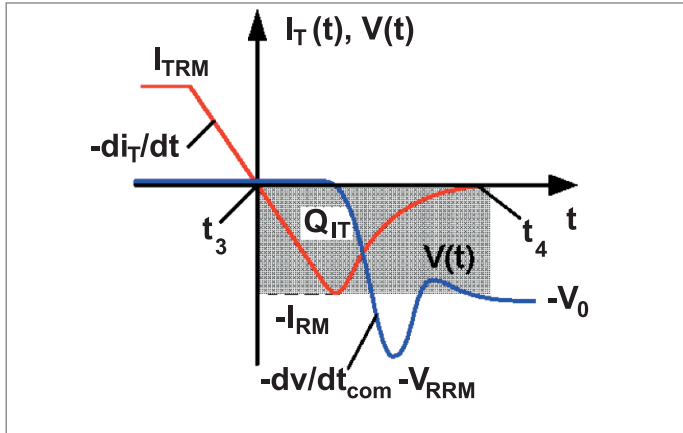

Fig. 1 Definitions of reverse recovery parameters for phase control thyristor.

Q_{rr}: Reverse recovery charge. Integral of the reverse current during commutation at given conditions starting at the 0-crossing of the reverse current, t_3, and ending when the reverse current goes back to 0, t_4, (See Figure 1) as expressed by equation 2.

$$Q_{rr} = \int_{t_3}^{t_4} i_T(t)dt \qquad \text{Eqn 2}$$

I_{RM}: Reverse recovery current. Peak value of the reverse recovery current at given conditions. See Figure 1.

I_{TRM}: Peak forward current. Maximum forward current through the thyristor. See Figure 1.

V_0: Commutation voltage. Quasi-stationary voltage driving the commutation. See Figure 1.

W_{on}: Turn-on switching energy. The energy dissipated during a single turn-on event. It is the integral of the product of anode current and the surplus of anode-cathode voltage due to the limited conducting area of the thyristor at triggering. This product is integrated from instant t_1, when the thyristor starts conducting, to instant t_2, when the plasma spread is finished and the whole thyristor area is conducting (see Figure 2) as expressed by Equation 3.

$$W_{on} = \int_{t_1}^{t_2} (i_T(t) \times (v_{AK}(t) - v_{AK(f ullarea)}(t)))dt \qquad \text{Eqn 3}$$

W_{off}: Turn-off switching energy. The energy dissipated during a single turn-off event. It is the integral of the product of anode current and anode-cathode voltage from the instant t_3, when the reverse recovery crosses the 0-line, to the instant t_4, when the reverse recovery is back to 0 (see Figure 1) as expressed by Equation 4.

$$W_{off} = \int_{t_3}^{t_4} (i_T(t) \times v_{AK}(t))dt \qquad \text{Eqn 4}$$

2 Turn-on losses

2.1 The turn-on process

Turn-on losses in a thyristor are generated when the device, just after triggering, has an anode to cathode voltage different from the static voltage drop, which the device would have, if the whole area was conducting. When the device is triggered (for recommendations about the gate triggering of a thyristor see application note 5SYA2034) this surplus voltage creates an additional energy loss. The turn-on energy W_{on} is composed of mainly two physical processes: (a) axial turn-on, where the anode and cathode emitters inject carriers and form a first latched conducting channel in the initially turned-on area of the thyristor, and (b) plasma spread, where the initially conducting channel spreads over the whole cathode area of the thyristor. In «normal» cases with di/dt of the order of 1 to a few tens of A/μs, axial turn-on is fast and causes only a small contribution to W_{on}. Figure 2 visualizes the turn-on process of a thyristor structure.
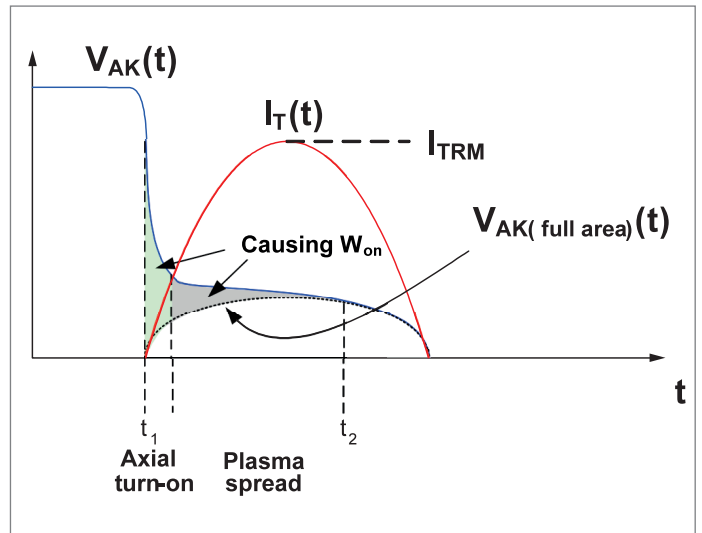

Fig. 2 Typical current and voltage transients at turn-on of a thyristor structure.

Depending on size, gate design and the current wave shape, the plasma spread can take as long as 2 – 3 ms, meaning that at short current pulses, the entire thyristor area may not be conductive before the device is turned off.

2.2 Determining the turn-on losses

Since it is hardly possible to measure all the needed data points for data sheet curves, a model for turn-on energy calculations was developed and calibrated using measured data.
For turn on, a simulation method including plasma spread is used. The model separates the thyristor areas, conducting and non-conducting, at every instance of time. The conducting area is assumed to have the same standard on-state voltage vs. current density behavior as the thyristor conducting over its full area. The remaining area takes no current. The conducting area is assumed to start at the inner cathode area contour with a minimum width and to propagate towards the periphery at a velocity proportional to the square root of the actual current density. When the conducting area has spread over the total thyristor area, the turn-on process has reached its end and the complete turn-on energy has been dissipated.

To calibrate this calculation method, comparisons of measured data were made as shown in Figure 3.
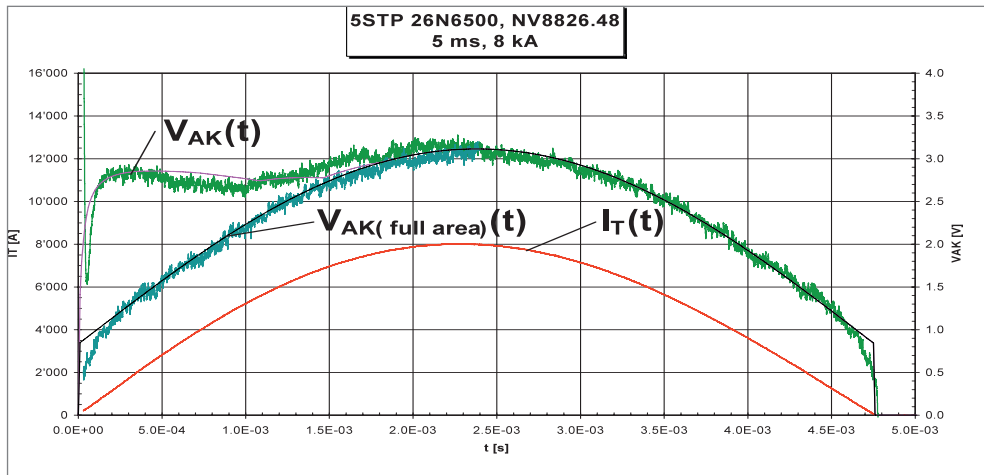

Fig. 3 Comparison of measured (green) and simulated turn-on transients (red and black) of 5STP 26N6500, using a half sine current waveform.

The calculated values were then used to create the data sheet curves for turn-on energy.

2.3 The data sheet curves for turn-on

The turn-on losses in the data sheets are presented as curves for turn-on energy for one turn-on event for sinusoidal current and for rectangular current, which strictly speaking is a trapezoidal current.

Common for both curves is the absence of V_{AK} as a parameter. The reason for this is that the voltage will break down during the short period of time during axial turn-on to a value that is almost independent of the voltage level at which the device was triggered, before the plasma spread phase starts. Since the current during the axial turn-on period is comparatively small, the influence of this part on the total losses is minute, and therefore the influence of the voltage at the instant of triggering can be disregarded. It should also be noted that the small additional turn-on energy caused by the discharge current emanating from the RC-snubber circuit is not included in the curves.

Figure 4 shows the turn-on energy per pulse, as a function of the peak value of the sinusoidal current, for several pulse widths. The dashed curve sections show that for this thyristor, short pulse widths in combination with low peak currents are not sufficient to get the device fully conducting before the current pulse is over.

Figure 5 shows the turn-on energy per pulse as a function of the DC-current level for different rates of rise of the on-state current.

3 Turn-off losses

3.1 The turn-off process

The turn-off process for a thyristor and the calculation of the RC-circuit are described in application note 5SYA2020. In the application note we describe different simulation methods for the turn-off energy and one of the methods is used to create the data sheet turn-off energy curves.

3.2 Determining the turn-off losses

Simulation of turn-off energies of a thyristor at moderate di/dt is easily possible under a number of assumed simplifications.
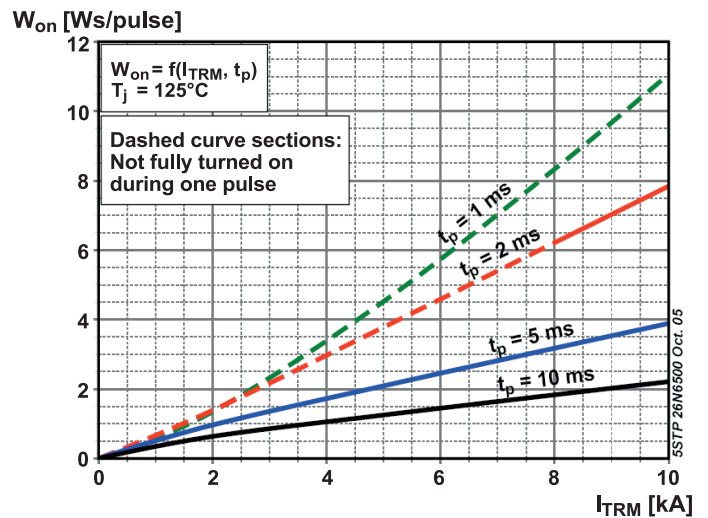

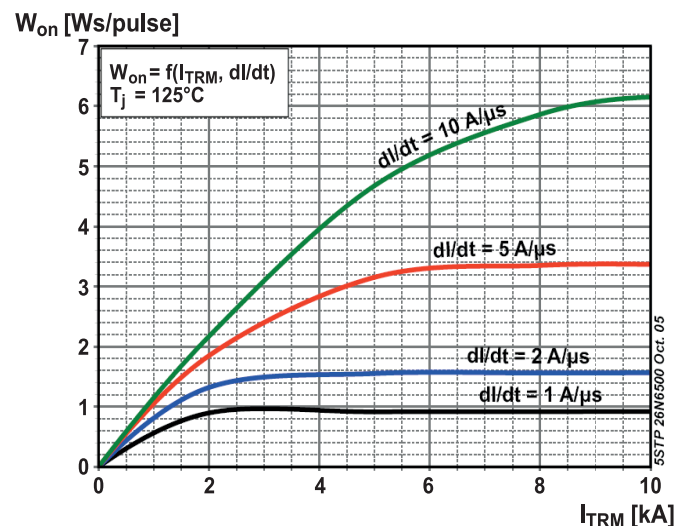Fig. 4 Turn-on energy, half sinusoidal waves.

Fig. 5 Turn-on energy, rectangular waves.

Here we are using the exponential recovery current model method described in 5SYA2020. The thyristor is considered as a current source during the turn-off process. At a given di/dt, the current decreases linearly through zero down to the reverse recovery current I_{RM} and from there decays exponentially with a time constant compatible with the given recovery charge Q_{rr}.
A simple circuit simulation can predict the reverse voltage transient and thus the turn-off energy. This simulation is performed using Pspice and is calibrated using a number of measurement points. To simplify the calculations and to obtain consistency, an RC-circuit with R = 22 Ω and C = 1.0 microfarad (μF) was chosen.
The calculated values were then used to create the data sheet curves for turn-off energy.

3.3 The data sheet curves for turn-off

The turn-off losses in the data sheets are presented as curves for turn-off energy for one turn-off event for sinusoidal current and for rectangular current, which strictly speaking is a trapezoidal current.
A specific RC-circuit, with values chosen to correspond to a typical RC-circuit as can be expected to be used in normal applications, is common for both curves. For RC-circuit values differing significantly from those used for the curves, the losses should be measured or calculated, preferably using the methods proposed in application note 5SYA2020.
The reverse recovery parameters of a thyristor have a fairly strong temperature dependency and consequently the turn-off losses also have a significant temperature dependency. The curves are given for 125 °C which is the worst case. For lower temperatures, the turn-off losses will be lower.
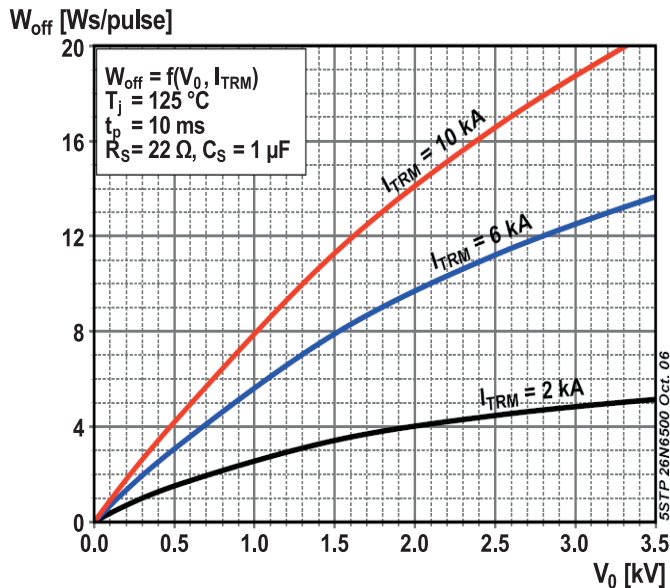

Fig. 6 Turn-off energy, half sinusoidal waves.

Figure 6 shows the turn-off energy per pulse, as a function of the commutation voltage V_0 for a few peak values of sinusoidal current pulses. The pulse width of 10 millisecond corresponds to 50 hertz. For 60 hertz the pulse width is 8.3 ms, and the losses will be about 15 percent higher due to the higher di/dt.
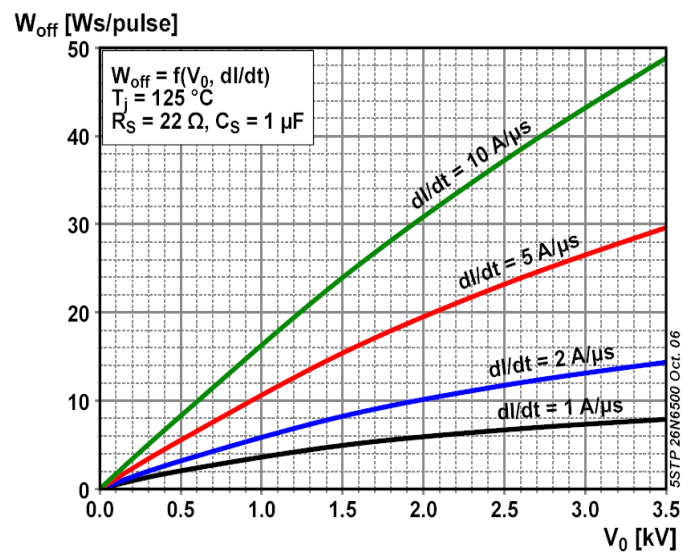

Fig. 7 Turn-off energy, rectangular waves.

Figure 7 shows the turn-off energy per pulse, as a function of the commutation voltage V_0 for different rates of decrease of the on-state current. The di/dt is given as a positive number in the curve although it is actually a rate of decrease. The influence of I_{TRM} is not included in these curves, as the influence is not very large for normal operating currents at given di/dt. The reverse recovery parameters and also W_{off} will decrease only at low currents.

4 Calculation of the total thyristor losses

When the commutation angle is stable the total thyristor losses can be calculated using equation 5 where f is the switching frequency for the thyristors.

$$P_{Total} = P_T + f * (W_{on} + W_{off})$$ E^{qn} 5

In addition to the on-state and the switching losses, the thyristor also has gate and blocking losses, but these are so small that they can be disregarded in almost all cases. Only for very special applications and operating conditions may the blocking losses need attention.
It should be noted that the data sheet values for VT_0, r_t, W_{on} and W_{off} are maximum values. It is quite unlikely that any device will have this combination, so calculations using the data sheet values will very probably introduce some margin in relation to an actual component.

5 References

1) IEC 60747 «Semiconductor Devices»
2) 5SYA2020 «Design of RC Snubbers for Phase Control Applications»
3) 5SYA2034 «Gate-drive Recommendations for Phase Control and Bi-Directionally Controlled Thyristors»

The application notes, References 2 and 3, are available at www. abb.com/semiconductors

6 Revision history

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