

Parameter selection of high power semiconductor for series and parallel connection

Although modern high power semiconductor devices have very high current and voltage ratings, some applications require either series or parallel connections of devices to obtain the full output voltage and output current of the equipment. Typical examples are HVDC (High Voltage Direct Current) transmissions and high current rectifiers for Aluminum smelters.



For best utilization of the equipment the devices to be used in parallel or in series must be specially selected so that they each take approximately the same share of current and/or voltage. This is both a question of design as well as of choice of components. In this application note, we look at the possible selections of line frequency thyristors and diodes for parallel or series connection that the power semiconductor manufacturer can offer.

1. Parameter banding of high power semiconductor devices

In principle it is possible for an OEM to select devices with the values of parameters such as on-state voltage V_F or recovery charge Q_{rr} within defined bands on the basis of the test reports provided by the semiconductor manufacturer. In practice, however, the banding is normally made by the manufacturer. When more than one band is used the manufacturer will add a band designation code (e.g. "A", "B", ...) to the device marking, and ship the devices as "matched sets".

1.1. Parameters normally used for banding

For series connection of line frequency thyristors and diodes the reverse recovery charge Q_{rr} is normally the most critical parameter, since it has a large influence on the dynamic voltage sharing, while the leakage current at the operating voltage is important for the static voltage sharing. Thyristors with different turn-on delay times will have different turn-on times, but in general the need for banding of delay times can be reduced or eliminated by using an appropriate gate triggering pulse. For parallel connection of line frequency thyristors and diodes the on-state voltage V_T / V_F is normally the most critical parameter since it has a large influence on the static current sharing. Again, for thyristors the spread of turn-on delay times is important, however also in this case the need for banding can be reduced or eliminated by using an appropriate gate pulse. For more information about the gate pulse requirements for thyristors see application note 5SYA 2034, "Gate drive recommendations for PCT".

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1.2. Limitations on the selection of band widths

For the various parameters of interest there are certain limitations to be considered when selecting the width of the bands. They include items such as the spread of parameter values in production, the measurement resolution and the measurement accuracy and precision. The manufacturer will always consider these limitations when determining the banding proposal. Often more than one band is necessary to cover the natural spread of values in production and therefore to avoid increases in the manufacturing costs and delays in deliveries. This is technically not a major obstacle since different branches in the equipment, as for instance in a B6C rectifier, normally can accommodate different bands. In these cases it is important to know how many devices are to be used in series or in parallel so that the correct number of devices in each group can be delivered as a “matched set”.

1.3. Application requirements

Special selections and parameter banding of the power semiconductors are not sufficient to guarantee a good performance of the equipment. Several external factors must be also considered.

Control:

The gate driver has a strong impact on the turn-on process of thyristors. By guaranteeing the simultaneous triggering of the devices it plays a pivotal part in ensuring a proper voltage and current sharing. For this purpose a strong gate triggering pulse is needed. For more details see the application note 5SYA 2034, “Gate drive recommendations for PCT”.

Thermal design:

The banding parameters are generally temperature dependent. It is therefore very important to ensure that the temperature of the heat sinks and of the cooling medium, and therefore the cooling efficiency, are the same for all the devices connected in series or parallel. It must also be ensured that for all devices the clamping pressure is uniform and the clamping force is within the limits specified in the data sheet. The values of the thermal resistance given in the data sheet are only valid if the clamping force is within the specified

range. Differences in clamping forces will lead to different thermal resistances and to different junction temperatures, again with detrimental effects on the current and voltage sharing.

Mechanical design and assembly:

The main objective of parallel connection is to achieve similar resistance and inductance values in all parallel current paths. Differences in the current paths will lead to uneven current sharing, forcing one or more devices to operate at a higher temperature than the rest. This can then lead either to the failure and possibly to the destruction of one or more devices due to overheating or, alternatively, it will result in an uneconomical solution, with only one or two devices used at their full capacity with the others in parallel connection being underutilized. A careful mechanical design and a suitable component selection are the only means of balancing the currents.

Together with a careful mechanical design it is also imperative to guarantee a proper mounting of all components. Improperly mounted devices can have high thermal and electrical contact resistances towards the heat sink, causing differences in voltage drops higher than the ones resulting from the actual spread among the devices, thus impeding a good current sharing.

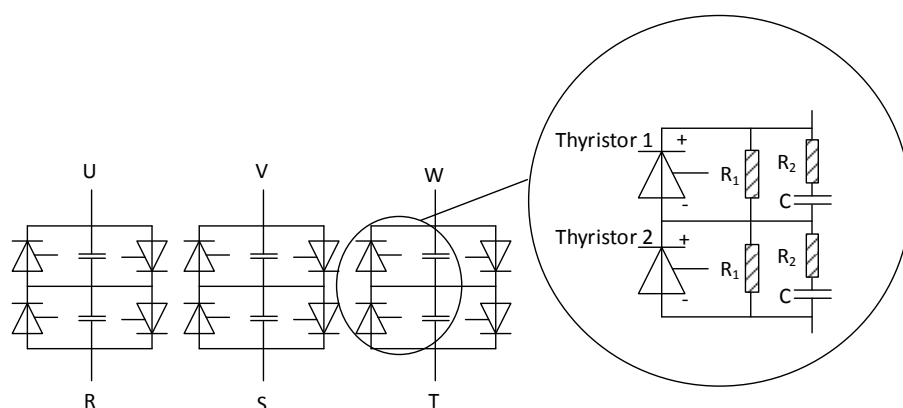
For more details about thermal design mechanical design and assembly see the application note 5SYA 2036 “Recommendations regarding mechanical clamping of press-pack high power semiconductors”.

2. Examples of parameter banding

In this section some simple examples will show the effect of the most common parameter banding schemes.

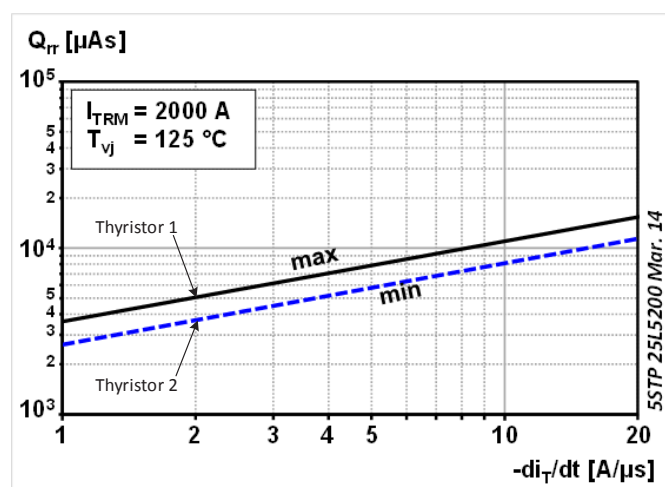
2.1. Voltage sharing in series connection

For a proper dynamic voltage sharing between thyristors or diodes in series connection we recommend a selection of based on the values of the reverse recovery charge Q_{rr} . The rationale for this recommendation is shown in the following example using the circuit of figure 1. In a real application many factors will influence the reverse recovery peak voltage. They include external factors as the commutation



01 Series connection of thyristors in an AC-switch

inductance and voltage, as well as internal factors as the softness of the device. Included in the circuit will also be additional components as resistor R1 that is used for static voltage sharing and R2 that is a damping resistor in the RC-snubber. For simplification we only calculate the difference in reverse recovery voltage between the two devices due to the difference in Q_{rr} and not the absolute voltages and we exclude the influence of items as R1 and R2 on this voltage difference. We consider the thyristor 5STP 25L5200 and assume $di/dt = -2 \text{ A}/\mu\text{s}$ at commutation. Thyristor 1 has the highest Q_{rr} value allowed by the data sheet, while thyristor 2 has the lowest Q_{rr} value, as shown in figure 2. At turn-off the difference in voltage between the two devices depends on the difference in Q_{rr} and on the snubber capacitance C. If we assume a $1 \mu\text{F}$ capacitor and the Q_{rr} values read in figure 2 ($5000 \mu\text{As}$ for thyristor 1 and $3600 \mu\text{As}$ for thyristor 2), we find:



02 Q_{rr} for device 5STP 25L5200

Thyristor 2 with lower Q_{rr} will stop conducting current earlier. It will therefore start taking up voltage earlier and end up with a higher

$$\Delta V \approx \frac{\Delta Q_{rr}}{C}$$

commutation voltage overshoot than thyristor 1. This unbalance results in a lower voltage margin and a higher risk of failure due

$$\Delta V \approx \frac{5000 - 3600 \mu\text{As}}{1 \mu\text{F}} = 1400\text{V}$$

to overvoltage for thyristor 2. To avoid this a larger capacitor C is needed. Unfortunately, this means additional losses and in an underutilization of thyristor 2.

To reduce the voltage difference ΔV we can either increase C or reduce ΔQ_{rr} . A reduction of ΔQ_{rr} is the preferred solution since a large

capacitor C is generally more expensive and more bulky.

In our example we could select as thyristor 1 a device with $Q_{rr} \approx 4300 \mu\text{As}$, near the center of the production spread, the difference in commutation voltage overshoot becomes:

$$\Delta V \approx \frac{4300 - 3600 \mu\text{As}}{1 \mu\text{F}} = 700\text{V}$$

In this way without any changes to the circuit the risk of over-voltages damaging the device is reduced substantially.

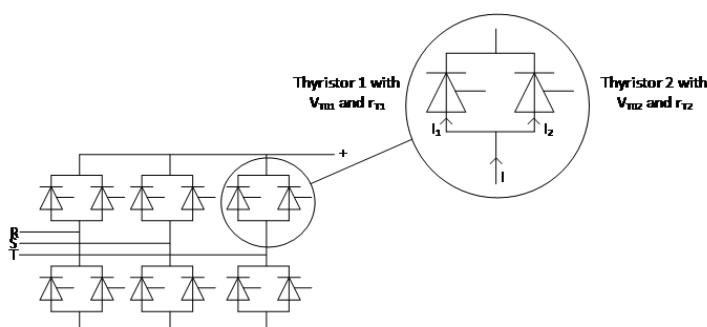
More about the dimensioning of snubber circuits for thyristors can be found in the application note 5SYA 2034, "Design of RC snubbers for PCT".

2.2. Current sharing between thyristors and diodes in parallel connection

A selection according to the on-state voltage drop is recommended to improve the current sharing between thyristor and diodes connected in parallel. A $V_{F\text{-band}}$ of 50 - 100 mV, normally measured at $T_{j\text{max}}$ and at a current close to I_{Fav} , is recommended. Since this often does not cover the entire production spread a solution with 2 to 5 $V_{F\text{-bands}}$ may be the most economical approach. We point out once again that a banding of the devices, however narrow it may be, will not compensate by itself alone an inappropriate mechanical solution or an inappropriate assembly of the various components.

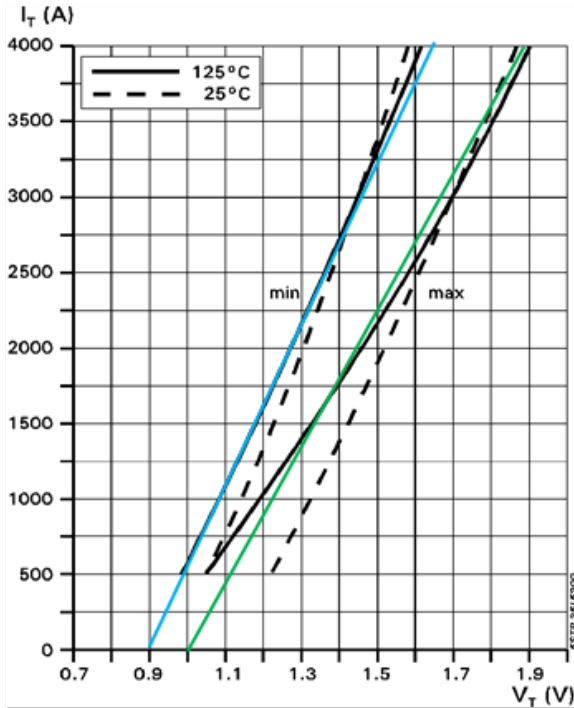
Let us work out an example to illustrate the importance of good matching. For a standard three-phase controlled rectifier with an output current of 5000 A we need in each branch two thyristors 5STP 25L5200 in parallel. The thermal resistance from junction to heat sink for this device at 120° rectangular current is 9.5 K/kW. The devices are mounted on air-cooled heat sinks with a thermal resistance from sink to ambient of 55 K/kW and the ambient temperature is 35°C . We assume that the mechanical layout and the assembly are identical for both devices. In a linear approximation the forward voltage drop is:

$$V_T = V_{T0} + r_T \times I_T$$



03 Definitions for the example calculations below

In the first example we assume that thyristor 1 has the highest on-state voltage V_T allowed by the data sheet, while thyristor 2 has the lowest V_T . A linear approximation to the on-state voltage curves gives for thyristor 1 $V_{T01} = 1.0$ V and $r_{T1} = 0.225$ mW (green line in Fig. 4) and for thyristor 2 $V_{T02} = 0.90$ V and $r_{T2} = 0.188$ mW (blue line in Fig. 4).



04 V_T without banding. Thyristor 1 with maximum V_T (green line) and thyristor 2 with minimum V_T (blue line)

The output current is the sum of the two thyristor currents and the on-state voltage drop is the same for both thyristors:

$$I = I_1 + I_2$$

$$V_{T01} + r_{T1} \times I_1 = V_{T02} + r_{T2} \times I_2$$

Entering the thyristor data and the total current we find:

$$5000 = I_1 + I_2$$

$$1.00 + 0.000225 \times I_1 = 0.90 + 0.000188 \times I_2$$

and therefore:

$$I_1 = 2034 \text{ A}$$

$$I_2 = 2966 \text{ A}$$

The difference in current between the two thyristors is more than 900 A.

To calculate the junction temperatures of the thyristors, excluding the quite low switching losses expected in normal rectification mode, we use the following equations valid for the connection in figure 3:

$$P_{loss} = (V_T \times I_T) / 3 = ((V_{T0} + r_T * I_T) \times I_T) / 3$$

$$T_j = T_a + P_{loss} \times (R_{THJH} + R_{THHA})$$

Thus:

$$P_{loss1} = ((1.00 + 0.000225 * 2034) \times 2034) / 3 = 988 \text{ W}$$

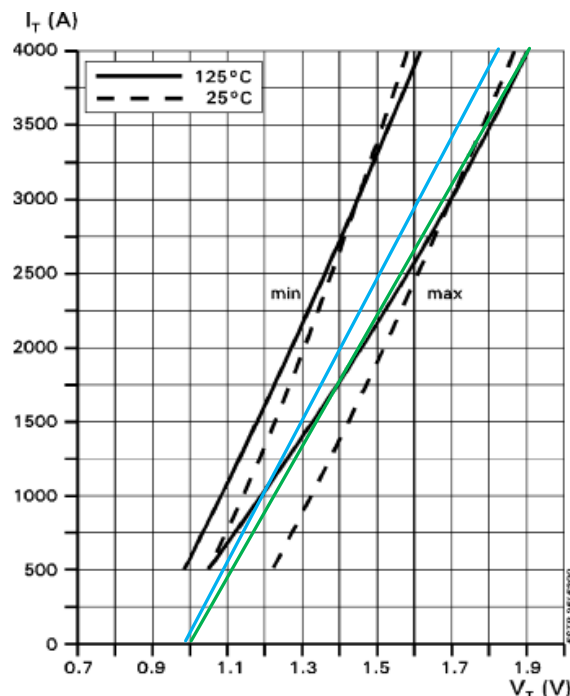
$$T_{j1} = 35^\circ\text{C} + 988 \times (0.055 + 0.0095) = 98.7^\circ\text{C}$$

$$P_{loss2} = ((0.90 + 0.000188 * 2966) \times 2966) / 3 = 1441 \text{ W}$$

$$T_{j2} = 35^\circ\text{C} + 1441 \times (0.055 + 0.0095) = 127.9^\circ\text{C}$$

Since the maximum allowed temperature for the 5STP 25L5200 is 125 °C thyristor 2 will overheat.

Compare this with the case illustrated in figure 5: The thyristors are now selected with V_T at 2500 A within a narrow band of 50 mV width. Thyristor 1 is the same as before (green line), with V_T at 2500 A equal to the maximum value allowed by the data sheet and $V_{T01} = 1.0$ V, $r_{T1} = 0.225$ mW. Thyristor 2 (blue line), has instead $V_{T02} = 0.98$ V and $r_{T2} = 0.210$ mW.



05 Specially selected thyristors, V_T with 50 mV banding at $I_T = 2500$ A

Using the previous equations, we can calculate the thyristor currents:

$$5000 = I_1 + I_2$$

$$1.00 + 0.000225 \times I_1 = 0.98 + 0.000210 \times I_2$$

Which gives:

$$I_1 = 2368 A$$

$$I_2 = 2632 A$$

The difference between the two thyristors is reduced to 264 A.

The maximum temperatures are now:

$$P_{loss1} = ((1.00 + 0.000225 \times 2368) \times 2368) / 3 = 1210 W$$

$$T_{j1} = 35^\circ C + 1210 \times (0.055 + 0.0095) = 113.0^\circ C$$

$$P_{loss2} = ((0.98 + 0.000210 \times 2632) \times 2632) / 3 = 1345 W$$

$$T_{j2} = 35^\circ C + 1345 \times (0.055 + 0.0095) = 121.7^\circ C$$

The junction temperature of both thyristors is now below the maximum allowed for the type 5STP 25L5200, $T_{jmax} = 125^\circ C$.

3. Considerations for assembly and spare part handling of banded devices

3.1. Assembly

The devices are normally grouped and shipped as “matched sets” with the parameters in question within the same band or bands. It is recommended keep the matched sets together until they are ready for assembly.

3.2. Spare parts

As long as original parts with the right band designation code are available from the origin delivery, and the assembly of all components is done with proper care the replacement of malfunctioning or failed devices should not present major problems.

If no more origin spare parts are available but the semiconductor device is still receivable from the manufacturer, it is recommended to order a new set of devices for the failed branch and use the replaced functional devices as spare parts for possible future failures in the origin branches. This, because of possible aging and therefore small changes in relevant parameters of the devices and because of a risk of small drift in measurement capability at the manufacturer over time.

Special caution is necessary when replacing obsolete devices or devices from another manufacturer are used in series or in paral-

lel connection. To guarantee the appropriate current and voltage sharing it is recommended to replace all the devices in any individual branch (arm) with specially selected ones.

The same recommendations hold for the replacement of devices connected in series or parallel when they are near the end of their expected lifetime. The operating life of the devices depends on a number of factors, among which the most important are the device size (area), the magnitude of the temperature excursions during operation as well as the number of power and temperature cycles that the devices have experienced. These factors can lead to small but relevant changes of some parameters, such as leakage currents and on-state voltage. A conservative approach would be to replace all the devices in any individual branch (arm) with specially selected ones.

4. Additional notes

4.1 Turn-off devices

In this application note we have only discussed thyristors and diodes. For considerations regarding parallel and series connection of turn-off devices, see application notes 5SYA 2032 “Applying IGCTs” and 5SYA 2098 “Paralleling of IGBT modules”.

5. Revision history

Version	Change	Authors
01	Dec 2016	Björn Backlund, Marco Rossinelli, Florian Weber, Jörg Berner