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AN6531
Guidelines for Series and Parallel Configurations of Press-Pack Thyristors and Diodes

Application Note

AN6531 February 2025 LN43892

***Abstract*—Series and parallel connections of high-power and high-voltage thyristors and diodes are crucial in achieving higher voltage and current ratings in high-power applications. However, inherent variations in device characteristics can lead to imbalanced voltage or current sharing, risking component failure and reduced system reliability. This application note outlines key guidelines for promoting uniform voltage and current distribution to enhance the performance and reliability of high-power systems.**

1 Introduction

In high-power electronic systems, achieving higher voltage and current capacities often necessitates the use of series and parallel connections of thyristors and diodes. Despite their advantages, such configurations are prone to imbalances that can affect system performance and reliability.

In series connections, unequal distribution of voltage arises due to factors such as variations in leakage currents (referred to as the off-state current, I_{DRM} and I_{RRM}, in thyristors and the reverse current, I_{RM}, in diodes), differences in gate-controlled delay time, t_{gd}, and disparities in reverse recovery charge, Q_{S}, among devices. These imbalances result in uneven voltage stress, potentially leading to component failure.

Conversely, in parallel connections, current sharing is affected by mismatched on-state voltage (V_{Tm}, for thyristors) or forward voltage (V_{Fm}, for diodes), discrepancies in dynamic turn-on behaviour, and induced voltages due to physical design. Such inconsistencies can cause certain devices to carry a disproportionate share of the current, risking thermal overload and damage.

V_{Tm} may also be referred to as V_{T}, and V_{Fm} as V_{F} in the literature and other Dynex application notes. For a detailed understanding of key concepts like leakage current, gate-controlled delay time, reverse recovery, and on-state voltage, readers are encouraged to refer to Dynex application note AN5950.

Understanding the challenges of parallel and series connection is vital for designing robust power systems. This application note examines these challenges in detail and serves as a foundation for implementing solutions to enhance reliability and performance.

2 Series Connection

Because each individual power semiconductor (for example, a diode or thyristor) can only handle a limited voltage—typically below 10 kV—multiple devices are connected in series for applications where the required voltage exceeds this limit. This series arrangement divides the total voltage among all devices, ensuring that no single semiconductor is overstressed. As a result, systems like High Voltage Direct Current (HVDC) transmission or high-voltage industrial drives can operate reliably without exceeding the voltage rating of any individual component.

2.1 Causes of voltage imbalance in series connections

When thyristors or diodes are connected in series, maintaining an even distribution of the off-state voltage is essential. Manufacturing tolerances and dynamic switching behaviours can lead to imbalances that overstress individual devices. The primary causes of these imbalances include:

- *Differences in leakage currents*: In the absence of external balancing networks, slight variations in leakage current among the series devices can result in uneven voltage distribution under both forward and reverse blocking conditions. As shown in **Figure 1**, even slight variations in the device blocking characteristics can lead to unequal voltage sharing across series-connected components, because each device must carry the same leakage current, I_{Lk}, in series connection.
- *Variations in gate-controlled delay time*: In a series-connected string of thyristors, any variation in gate-controlled delay time means that some thyristors will turn on slightly later than others. As a result, the last thyristor to switch will remain in the off-state longer and momentarily be subjected to the bulk of the total voltage, which frequently exceeds its blocking capability.
- *Discrepancies in reverse recovery charge*: As shown in **Figure 2**, deviations in reverse recovery charge lead to different reverse recovery times, and peak reverse recovery currents, causing individual devices to experience the off-state voltage at slightly different moments. As shown in **Figure 2**, the first thyristor/diode to turn off will momentarily be exposed to the bulk of the total voltage.

The voltage imbalance introduced by a difference in Q_{s} between two series-connected devices is approximately estimated by (1). In (1), C_{s} is the capacitance of the parallel snubber circuit (see Dynex application note AN6481 for details on snubber circuits in thyristors and diodes).

$$\Delta V \approx \frac{\Delta Q_{\mathrm{s}}}{C_{\mathrm{s}}} \qquad (1)$$

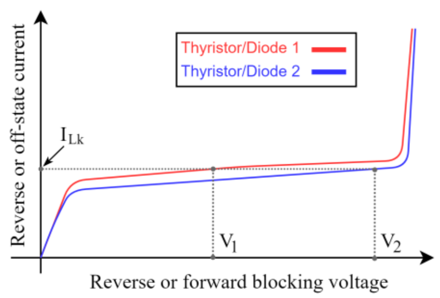


Figure 1. Voltage imbalance caused by variations in leakage current characteristics.

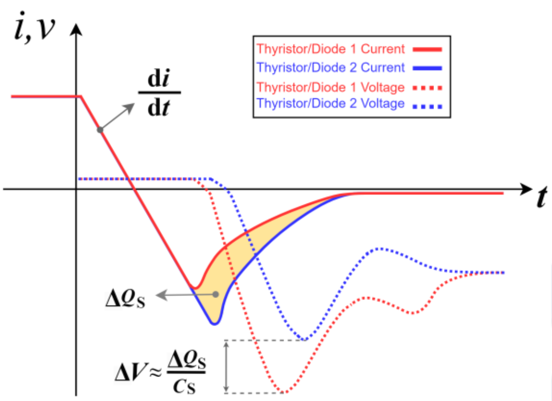


Figure 2. Voltage imbalance caused by variations in turn-off characteristics.

- *Variations in mechanical construction*: When power devices are placed in series, it is crucial to maintain consistent electrical paths for each device; otherwise, any asymmetry in their connections can introduce uneven commutation inductances or parasitic resistances. The mismatched inductances directly influence di/dt, which impacts the reverse recovery behaviour. As a result, one device might experience higher voltage stress and switching losses, while another might see reduced stress—leading to imbalanced performance, increased chances of device failure, and potential reliability issues across the entire stack.
  Improper assembly—such as uneven mounting pressure, asymmetric location within the stack or misalignment—causes unequal thermal dissipation and higher temperatures in some diodes/thyristors. Since reverse recovery characteristics and leakage current are both temperature dependent, hotter devices may exhibit higher leakage currents or altered recovery times, leading to an unbalanced off-state voltage distribution.

2.2 Voltage balancing guidelines for series connections

Ensuring each device in a series string shares the off-state voltage evenly requires careful consideration of both steady-state and dynamic conditions. Below are several recommended practices to maintain reliable operation:

2.2.1 Steady-state voltage balancing

Key aspects of voltage balancing for steady-state voltage during the off state include matching leakage currents and using external balancing resistors.

- *Leakage current:* As mentioned, the main cause of unbalanced voltage distribution in series-connected power semiconductor devices is the variation in leakage current. Therefore, it is advisable to select and match devices with similar leakage currents for series connection.
  Leakage current is measured as part of routine production testing, and Dynex provides the leakage current values for its diodes and thyristors at 25°C and maximum junction temperature under each device's maximum blocking voltage. These values are provided with the diodes and thyristors when they are shipped to customers. If required, Dynex can supply banding to match devices with similar leakage current. When multiple bands are utilised, Dynex includes a band designation code (such as "A", "B", etc.) on the device marking to allow customers to easily differentiate between them.
- *Balancing resistor*: To ensure uniform voltage sharing in series-connected devices, it is important to use an external circuit in addition to (or instead of) matching the leakage current.
  An RC snubber connected in parallel with each device is often sufficient to maintain balanced voltage in the off-state. However, when high DC voltage is applied for extended periods, it is highly recommended to also include a resistor in parallel with each thyristor/diode, as shown in **Figure 3**, to externally force a steady state voltage symmetry. By establishing a defined current path, these resistors help reduce voltage imbalances caused by slight variations in the leakage currents.
  To ensure effective operation, in a straightforward design approach, the resistance should typically be sized so that the balancing resistor carries around two to five times the device's leakage current at the operating temperature and voltage. Alternatively, for a more refined design, (2) from [1] can be utilised to determine the maximum allowable resistance value, R.

$$R \leq \frac{n(1-a)V_D - (1+a)(1+b)V_s}{(n-1)(1-a^2)I_{\mathrm{Lk}}} \quad (2)$$

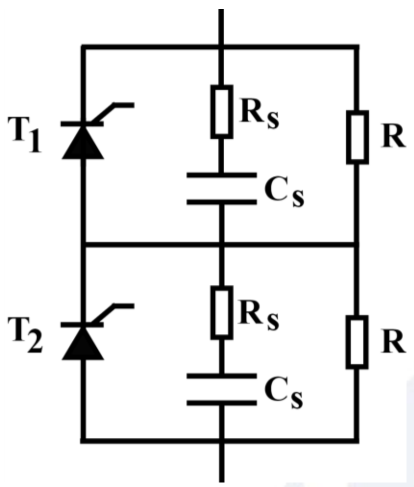


Figure 3. Voltage balancing circuit in series connection.

In (2), n, a, b, V_D, V_s, and I_{Lk} represent the number of devices, the resistor tolerance, the string voltage tolerance, the rated voltage of each device, the total string voltage, and the maximum leakage current of the device current at the operating temperature, respectively. The balancing resistor consumes power, so it is preferable to use a resistor with the highest possible resistance.

2.2.2 Dynamic voltage balancing during turn-on

Key aspects of voltage balancing for transient voltage during the turn-on state include synchronised triggering (applicable only to thyristors) and the use of a snubber capacitor.

- *Synchronised triggering*: To reduce differences in gate-controlled delay times, all thyristors in the series chain should receive simultaneous, high-amplitude, and sharply rising trigger pulses (e.g., 4–10 times the rated gate trigger current, with a rise time below 1µs, ideally below 0.5 µs). This approach narrows the variation in gate-controlled delay time, ensuring that no single device remains in the off-state long enough to bear a disproportionate share of the total voltage.
  It is important to consider safety margins and potential risks, such as thermal stress on the gate junction and increased Electromagnetic Interference (EMI), when applying high gate current amplitudes during synchronised triggering.
- *Limiting voltage rise on the last thyristor to switch*: The thyristor or diode that completes turn-on last will momentarily face a higher reverse or off-state voltage. It should be ensured the blocking voltage of the last thyristor to turn on in a series connection increases slowly. Often, properly designed RC snubbers will slow the voltage transition sufficiently. If not, incorporating saturable inductors or refining the circuit layout may be necessary to prevent excessive voltage stress.

2.2.3 Dynamic voltage balancing during turn-off

Key aspects of voltage balancing for transient voltage during the turn-off state include matching reverse recovery charge and snubber capacitor.

- *Matching reverse recovery charge*: As mentioned, differences in reverse recovery charge, Q_s, among devices can cause uneven turn-off voltage distribution. To combat this, thyristors or diodes may be grouped by matching Q_s, ensuring they exhibit similar reverse recovery behaviour. This consistency further stabilises voltage sharing during the turn-off phase. The Q_s of thyristors and diodes is not routinely measured at Dynex and is only provided upon request. In addition, banding based on Q_s is also available upon request.
  For series connections, it is important to note that Q_s has the most significant impact and should be carefully matched.
- *Snubber circuit*: As shown in (1), the voltage imbalance between series-connected diodes or thyristors during turn-off transients is influenced by the capacitance of the RC snubber circuit. Properly sizing each RC snubber reduces sudden voltage shifts during current interruption, enabling a smoother transition to the off-state for all devices.
  To ensure proper voltage balancing during the turn-off transition in series-connected thyristors/diodes, a conservative design approach using (3) from [1] can be applied to determine the minimum snubber capacitor value (C_s).

$$C_s \geq \frac{(n-1)\Delta Q_s}{(1-c)(nV_D-(1+b)V_s)} \qquad (3)$$

where c and ΔQ_s represent the capacitor tolerance and the maximum difference in the reverse recovery charge of the devices in the string, respectively. Higher capacitance results in increased losses, thus it is advisable to use a capacitor with the lowest possible capacitance.

It should be noted that the primary role of the snubber capacitor is voltage spike suppression during the reverse recovery. Therefore, it should be emphasised to first focus on designing the RC snubber circuit to address this primary function, following Dynex application note AN6481 or a similar methodology. Once the RC circuit is designed, it should also be verified that the capacitor value meets the requirements of (3) to ensure voltage balancing.

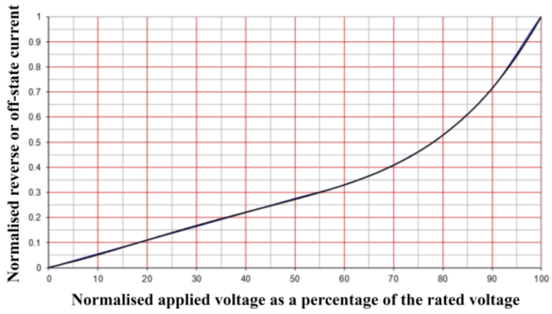
2.2.4 General considerations for voltage balancing

A well-balanced mechanical design is crucial to ensure equal voltage sharing among series-connected thyristors or diodes during both dynamic and steady-state phases. The electrical layout for all devices should be as symmetrical as possible to ensure uniform exposure to d*i*/d*t*, d*v*/d*t*, gate pulse, and voltage variations. The thermal dissipation for all devices should be as uniform as possible—additional heat sinks may be added between the series connected devices if needed—and each device must be clamped with consistent pressure to avoid uneven mechanical stress or thermal contact.

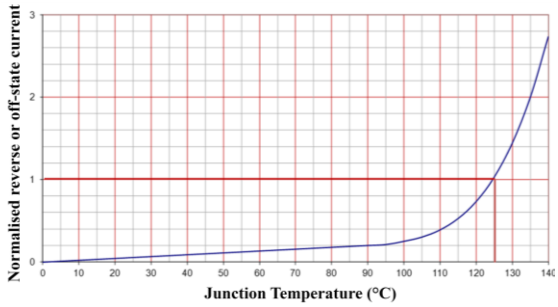
Datasheets typically specify the maximum leakage current at the rated voltage and peak junction temperature. It is advisable to design the balancing circuit based on these values to account for the worst-case scenario. However, if optimal power density is necessary, balancing resistors should be chosen based on the leakage current at the expected operating temperature and blocking voltage. A suitable safety margin should still be applied. **Figure 4(a)** and **Figure 4 (b)** (from Dynex Application Note AN6161) can be used to approximate how leakage current varies under different blocking voltages and operating temperatures. Please note that these graphs provide approximate values, and the actual values may have significant deviations.

3 Parallel connection

Each individual power semiconductor device, such as a diode or thyristor, has an average current handling limit—typically below 8 kA. For applications requiring currents beyond this threshold, multiple devices are connected in parallel. This configuration distributes the total current among all the devices, preventing any single semiconductor from being overstressed. Such parallel arrangements are commonly used in high-power applications, including HVDC systems, large industrial drives, rail traction systems, and power converters in renewable energy installations, where reliable current sharing is critical for system performance and longevity.



(a)



(b)

Figure 4. Variation of leakage current with (a) blocking voltage and (b) junction temperature.

3.1 Causes of current imbalance in parallel connections

When thyristors or diodes are connected in parallel, maintaining an even distribution of the current is essential. Manufacturing tolerances and dynamic switching behaviours can lead to imbalances that overstress individual devices. The primary causes of these imbalances include:

- *Differences in on-state/forward voltage*: In the absence of external balancing networks, slight variations in on-state voltage among parallel thyristors and diodes can result in uneven current distribution. As shown in **Figure 5**, even minor differences in device characteristics can lead to unequal current sharing, as each device in a parallel connection must maintain the same on-state voltage.
- *Variations in dynamic turn-on behaviour*: Discrepancies in the dynamic turn-on behaviour of parallel thyristors and diodes can lead to unequal current sharing due to variations in their gate-controlled delay times, junction characteristics, and voltage drop rates (d*v*/d*t*). When one thyristor turns on

faster than others, it momentarily bears the majority of the current while the others remain in their off-state.
It is important to also note that all RC-snubbers of the parallel branches will discharge across the thyristor that triggers first, causing it to turn on at a high di/dt, which can potentially lead to device di/dt failure.

- *Variations in mechanical construction*: Unequal current sharing in parallel thyristors and diodes can arise from mechanical design factors, such as different conductor lengths or mounting positions, which introduce uneven inductances, resistances, and voltages. This can cause certain devices to carry more current than others.
Improper assembly—such as uneven mounting pressure, asymmetric location within the stack or misalignment—causes unequal thermal dissipation and higher temperatures in some devices. Since a thyristor and diode's electrical parameters (like on-state voltage) change with temperature, these hotter devices may draw different current.

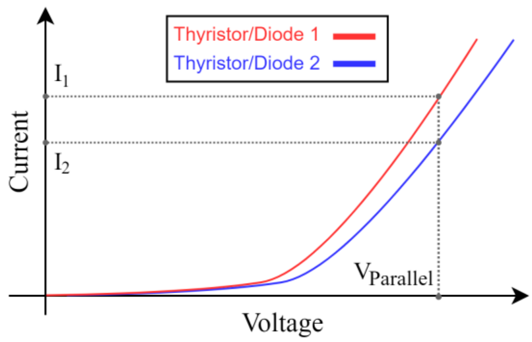


Figure 5. Current imbalance caused by variations in on-state/forward voltage.

3.2 Current balancing guidelines for parallel connections

Ensuring each device in a parallel string shares the on-state current evenly requires careful consideration of both steady-state and dynamic conditions. Below are several recommended practices to maintain reliable operation:

3.2.1 Steady-state current balancing

Key aspects of current balancing for steady-state current during the conducting state include matching on-state voltage and using external balancing resistors or inductors.

- *On-state voltage:* As mentioned, the primary cause of unbalanced current distribution in parallel-connected power semiconductor devices is the variation in the on-state voltage. To minimise this issue for the parallel operation, it is advisable to select and match devices with similar on-state voltage, ideally sourced from the same production batch. However, practical limitations (see Section 5) can make this approach unfeasible in some cases.
On-state voltage is routinely measured during production testing, and Dynex provides these values for its diodes and thyristors at maximum junction temperature under a current close to the maximum average current. These values are supplied to customers along with the devices upon shipment. Additionally, Dynex offers banding services to group devices with similar on-state voltage, ensuring better compatibility for parallel configurations. When multiple bands are used, Dynex includes a band designation code (e.g., “A”, “B”) on the device marking for easy identification by customers. For optimal parallel performance, a banding range below 100 mV is recommended (the smaller, the better). However, banding range is subject to certain practical limitations (see Section 5).
- *Balancing resistor or coupled inductor*: To achieve equal current sharing in the steady state for parallel-connected thyristors or diodes, it is important to maintain equal slope resistances as much as possible. Adding series resistances to the individual branches of the parallel devices, such as fuses and resistors, can enhance current symmetry. However, these resistors and fuses must be closely matched, as mismatched resistances could worsen the current imbalance.
Coupled inductors also play a significant role by dynamically correcting imbalances in current between branches. When one device carries more current, the coupled inductor generates an opposing voltage in that branch, reducing its current, while simultaneously increasing the current in the branch with lower current flow.
Adding individual resistors and coupled inductors to equalise current sharing introduces significant complexity and losses to the circuit. As a result, these methods are generally not recommended unless absolutely necessary. The design and

calculation of coupled inductors and resistors are beyond the scope of this application note; for more details, refer to [1], [2], [3].

3.2.2 Dynamic current balancing during turn-on

Balancing resistors or coupled inductors also help with dynamic current balancing. The other key aspects of voltage balancing for transient current during the turn-on state include synchronised triggering and the use of a pulse train triggering.

- *Synchronised triggering*: To reduce differences in dynamic turn-on behaviours, all the parallel thyristors should receive simultaneous, high-amplitude, and sharply rising trigger pulses (e.g., 4–10 times the rated gate trigger current, with a rise below 1μs, ideally below 0.5 μs) while considering thermal stress on the gate and EMI. This approach reduces variations in gate-controlled delay times, ensuring that no single device switches on significantly earlier than the others and ends up carrying a disproportionate share of the total current.
  In this context, the gate trigger current, I_{GT}, is also a critical parameter, as it determines the minimum gate current required to turn on a thyristor reliably. At Dynex, I_{GT} is routinely measured during the production tests, and it can be used to match parallel thyristors effectively.
- *Pulse train triggering*: For large thyristors or those with high blocking voltages, there is a risk that some devices may revert to their forward off-state after triggering if the on-state current density is too low—especially when the other conducting devices in parallel reduce the anode-cathode voltage to the on-state levels. Repetitive triggering can help prevent this issue by ensuring all thyristors remain actively conducting, thereby avoiding overloading the already conducting thyristors when the load current increases.

3.2.3 General consideration for current balancing

A balanced mechanical design is important to ensure equal current sharing in parallel-connected thyristors/diodes during both dynamic and steady state phases. First, the layout should be as symmetrical as possible so that each device has similar conductor lengths and paths, thereby minimising differences in parasitic inductances and resistances. Second, all devices should be mounted on a common heat sink with uniform pressure and contact area to avoid variations in thermal and electrical contact resistances (e.g., see **Figure 6** for three parallel devices [3]).

Finally, in parallel connections, it is important to apply a derating factor to the maximum current capability of the devices to maintain an adequate safety margin. As the number of parallel devices increases, a higher derating factor should be used to account for greater variability in current sharing.

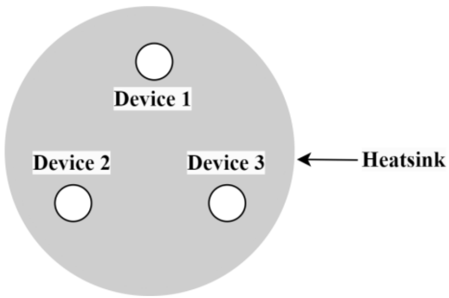


Figure 6. Symmetric arrangement.

4 Replacing devices in series and parallel configurations

Devices in power electronic systems may require replacement for various reasons, including component failure, degradation over time, or system upgrades. Failures can arise from factors such as electrical overstress, cosmic radiation, thermal fatigue, or adverse environmental conditions. Additionally, aging effects like wear-out mechanisms and parameter drift can compromise performance and reliability. System enhancements or changes in operating conditions might also necessitate replacing outdated components with more advanced or compatible ones to ensure optimal performance.

When replacing faulty semiconductor devices, it is best to use original components with the correct banding where possible. If these are unavailable, procuring and installing a complete matched set of new devices (and keeping the functioning older ones as spares) helps maintain consistency.

Devices nearing the end of their lifespan may experience parameter changes due to thermal cycling, power fluctuations, and prolonged usage. To mitigate these risks, replacing all devices in the branch with matched replacements is a prudent strategy for ensuring consistent performance and reliability.

When using upgraded, obsolete, or mixed-manufacturer devices, ensure proper current and voltage balance. Replace all devices in a branch with matched ones for reliable operation.

Please refer to Dynex application notes 6142 and AN6143 for more information on replacing devices in parallel and series configurations.

5 Final Remarks

This application note has outlined the challenges and solutions for achieving effective voltage and current balancing in series and parallel configurations of thyristors and diodes. Additionally, it has highlighted the importance of device selection to minimise imbalances in high-power applications. Among the various parameters, matching (banding) Q_s is vital for series connections to ensure balanced voltage sharing, while V_{Tm} or V_{Fm} matching is essential for parallel connections to achieve uniform current distribution.

Selecting suitable parameter bands requires careful consideration of production variability as well as the resolution, accuracy, and precision of measurement tools. These factors significantly influence manufacturers' banding strategies and capabilities, making very precise matching generally impractical. For example, it may not be feasible to reduce on-state voltage variation below 50 mV, and the limited availability of devices from a single batch makes it impractical to ensure matching both the on-state voltage and the batch number for large orders.

In many cases, a single band width is insufficient. Instead, multiple bands may be necessary to account for normal production fluctuations and to minimise additional costs or delays in shipping. From a technical perspective, assigning multiple bands is typically not problematic, as different sections of the equipment—for example, the branches in a B6C converter—can accommodate different bands without issue.

6 References

[1] B. W. Williams, *Power Electronics: Devices, Drivers, Applications and Passive Components*. 1992.

[2] R. Hermann, S. Bernet, Y. Suh, and P. K. Steimer, 'Parallel Connection of Integrated Gate Commutated Thyristors (IGCTs) and Diodes', *IEEE Trans. Power Electron.*, vol. 24, no. 9, pp. 2159–2170, Sep. 2009, doi: 10.1109/TPEL.2009.2021837.

[3] M. Ramamoorty, *An introduction to thyristors and their applications*. Macmillan, 1978.

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