



## Challenges to Paralleling

### Static Current Mismatch

Static current mismatch is a mismatch in current between parallel parts after switching transients have settled. This is especially a concern for parts with inherent thermal instability, or in other words, parts with a negative temperature coefficient of on-resistance as in older Si diodes and punch-through IGBTs. Parts with a negative TC can be successfully paralleled if the part-to-part variation (distribution) of on-resistance is sufficiently narrow (binned parts) and margin is added to account for inevitable current mismatch.

There is a widespread myth that a positive temperature coefficient in on-resistance forces uniform current sharing and consequently facilitates paralleling. In reality, a positive TC *only ensures thermal stability*. The belief in the power of a positive TC over current sharing is reinforced by the narrow parameter distributions of modern power semiconductors, including SiC JFETs, SiC MOSFETs, field stop IGBTs, etc. It is parameter distribution and common heat sinking that determine static current sharing.

### Dynamic Current Mismatch

Dynamic current mismatch is caused by part-to-part threshold voltage variation that is inherent in MOS-gated and JFET devices, by asymmetry in current loops, and by variation in propagation delay between gate drivers if applicable. A part with lower threshold voltage switches on sooner and off later and consequently has more hard-switching loss. This is more of a concern at very high switching frequencies.

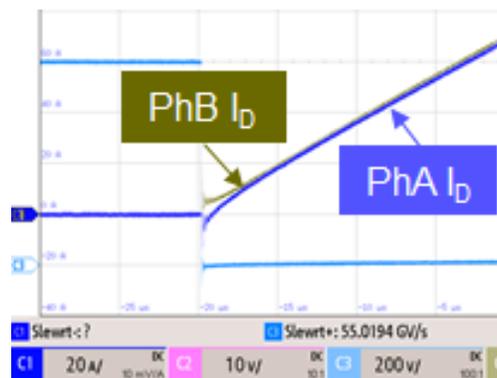


Figure 2 Dynamic current mismatch due to threshold voltage mismatch

Figure 2 shows the dynamic mismatch at turn-on of two parallel cascodes. The current mismatch quickly shrinks, which is typical because steady state current sharing is dominated by  $R_{DS(on)}$ . Using maximum  $R_{DS(on)}$  and  $R_{\theta JC}$  datasheet values in calculations provides safety margin to accommodate static and dynamic current mismatch when paralleling.

### Parallel Oscillation

Parallel oscillation can be a problem with high gain, fast switching parts. This is especially a concern with the SiC JFET cascode (hereafter known as cascode for short) due to two active devices inside: a low-voltage Si MOSFET and a SiC JFET. Sustained parallel oscillation, as in Figure 3, risks device failure due to exceedingly high switching loss. It can be difficult to observe the oscillation with an oscilloscope. Waveforms can look fine, and within only a couple switching cycles, oscillation can begin. There are various possible causes for this, such as variations in load current, voltages, and temperature. It is mainly caused by the fast switching of the cascode, especially at high current when  $di/dt$  and  $dv/dt$  become even faster.

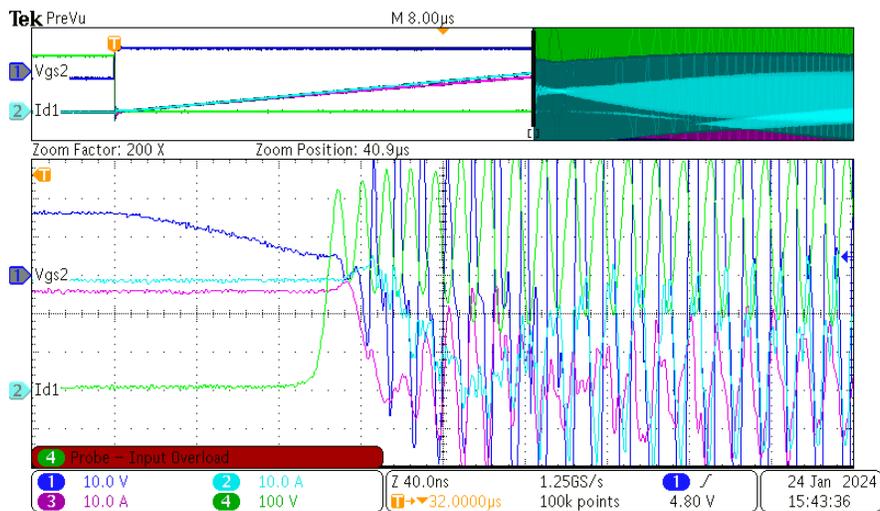


Figure 3 Two parallel cascodes going into sustained parallel oscillation during double-pulse testing

Despite the complexity, it is useful to analyze the operation of two parallel cascodes including relevant capacitances and inductances, as shown in Figure 4 for cascodes with a Kelvin-source pin. The TO-247-3L and D2Pak-3L packages have no Kelvin-source pin, and this situation is discussed later.

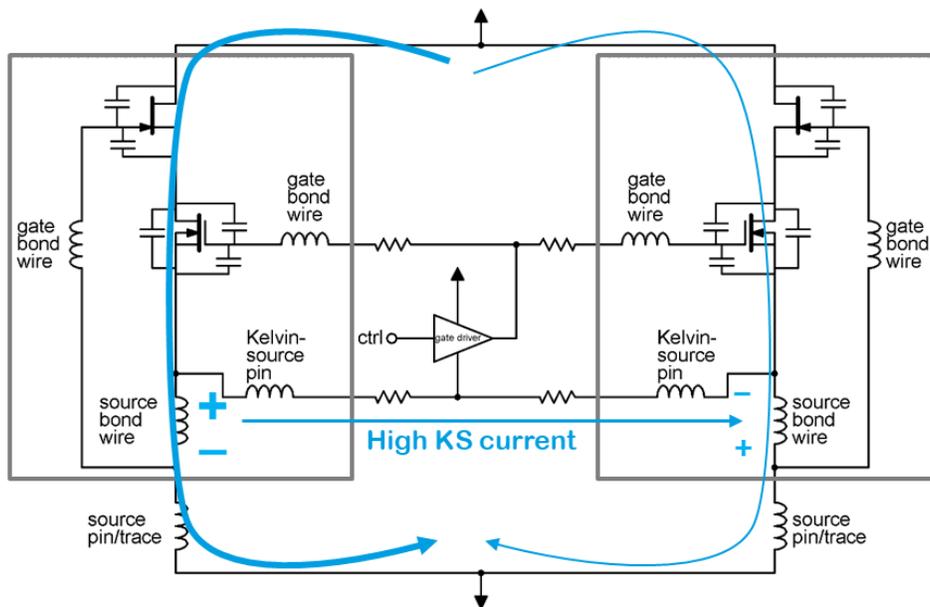


Figure 4 Two parallel cascodes turning on with dynamic current mismatch

As already mentioned, dynamic current mismatch is practically unavoidable due to variations in threshold voltages, and possibly compounded by asymmetry in the circuit layout. In Figure 4, we can imagine two cascodes switching on, with the one on the left switching on slightly sooner than the one on the right. Higher current in the left cascode causes higher voltage to develop across the left side source inductances. In extreme cases, current in the right cascode can flow momentarily in the reverse direction. In any case, the source voltage mismatch induces current to flow through the Kelvin-source connections, as indicated in Figures 4 and 5.

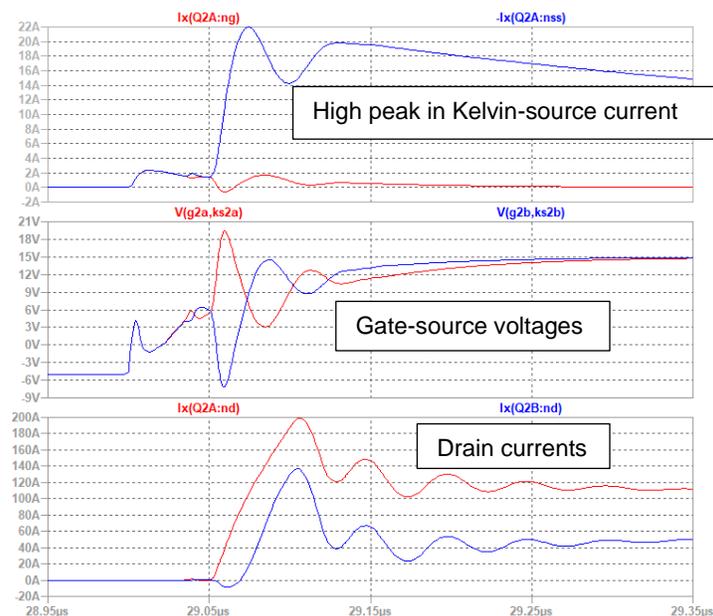


Figure 5 Top: Kelvin-source current greatly surpasses gate current. Middle and bottom:  $V_{GS}$  and  $I_D$  of each cascode

Figure 5 shows the simulation results of two parallel UF3SC120009K4S hard-switching on with an inductive load. Each part has a 680 pF plus 4.7  $\Omega$  drain-source snubber. One cascode has 10% lower than typical and the other 10% higher than typical threshold voltage for both the JFET and MOSFET, thus inducing dynamic current mismatch. This is a plausible situation, even if unlikely. There is no added Kelvin-source impedance. The top graph shows high peak Kelvin-source current greatly surpassing the cascode gate current. Ideally, the gate and Kelvin-source currents are equal in magnitude (differential). The cascode gate-source voltages in the middle graph show out of phase ringing, a tell-tale indicator of imbalanced gate-source voltages, which under certain circumstances can escalate into a sustained, destructive parallel oscillation. The bottom graph of Figure 5 shows the mismatch in drain currents that ultimately cause the large Kelvin-source current. The dynamic current mismatch settles to near zero steady state.

Source and/or drain inductance mismatch also causes dynamic mismatch. Combining this with random threshold voltage variations can make parallel oscillation occur randomly, especially with a cascode because both JFET and MOSFET threshold voltage variation cause dynamic current mismatch.

A seemingly simple solution is to move all the gate loop resistance to each Kelvin-source connection, or as much as possible if different turn-on/off resistances are used, as shown in Figure 6(b). This can however result in sustained oscillation. Why? The peak Kelvin-source current is certainly reduced by the increased Kelvin-source resistance. However, consider that the charge to/from the gate-drain capacitance of the cascode's MOSFET is through the cascode's gate resistor. Less gate resistance allows higher peak gate current, higher peak  $dV_{DS}/dt$  of the MOSFET, and consequently higher peak  $dV_{GS}/dt$  of the JFET. Furthermore, the gate resistance provides damping for the MOSFET output capacitance – source inductance and other LC tank circuits. Moving all gate loop resistance to the Kelvin-source connection removes damping from the cascode's MOSFET gate, which combined with a large mismatch in gate versus Kelvin-source current can result in oscillation.

How can we maximize gate damping while minimizing the mismatch between gate and Kelvin-source currents? First, we leave the gate resistance for each cascode in the gate connection instead of in the Kelvin-source connection. We need to maximize damping of each gate, so no common gate resistor should be used, see Figure 6(a). Put all gate resistance in each cascode gate connection. Follow the [User Guide](#) recommendations of gate resistor values for initial testing. Second, we could add a common-mode choke (CMC) or differentially coupled inductors to the gate and Kelvin-source connections, as in Figure 7(a). This forces the gate and Kelvin-source current magnitudes to match more closely. Experiments demonstrated that sustained oscillations were eliminated with a CMC impedance of at least 100  $\Omega$  at 10 MHz, such as Pulse AWCU0045322623TT2, or Bourns SRF4530A-220Y, or similar. Exact values are not critical; especially because the CMC has no effect on delay times. Third, snubbers must be installed when paralleling. In addition to reducing switching slew rates, a snubber also damps ringing with the snubber resistor. Hence adding snubbers greatly reduces the likelihood of oscillation. Finally, minimize the gate resistance by relying on the snubbers to set the switching speed as much as possible. This is counterintuitive but is explained in the Cascode Primer. The User Guide gate resistor recommendations are

minimal values for clean switching. Parallel parts can share a common snubber, or there can be a separate snubber for each cascode. The important points are layout symmetry and minimum inductance in the snubber connections.

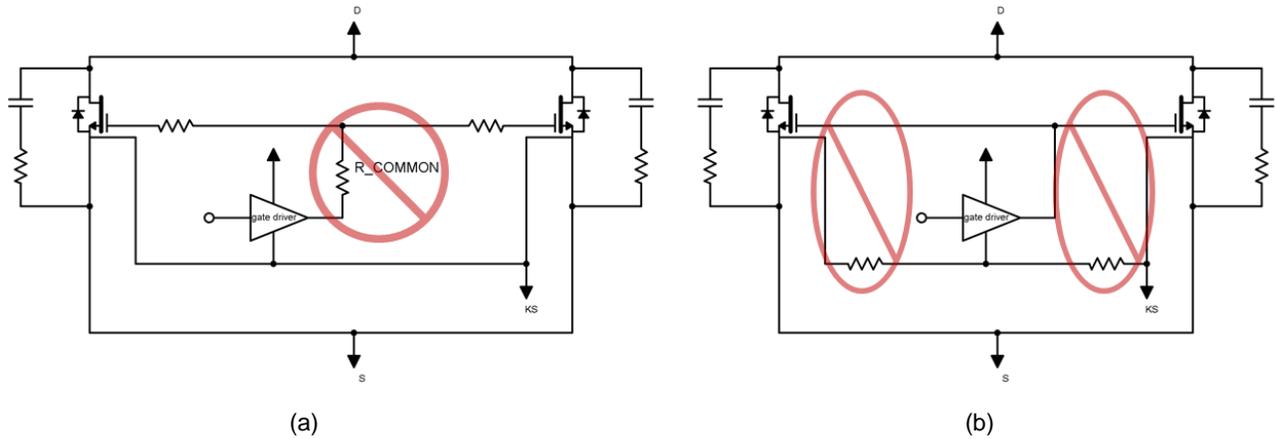


Figure 6 Things to avoid when paralleling

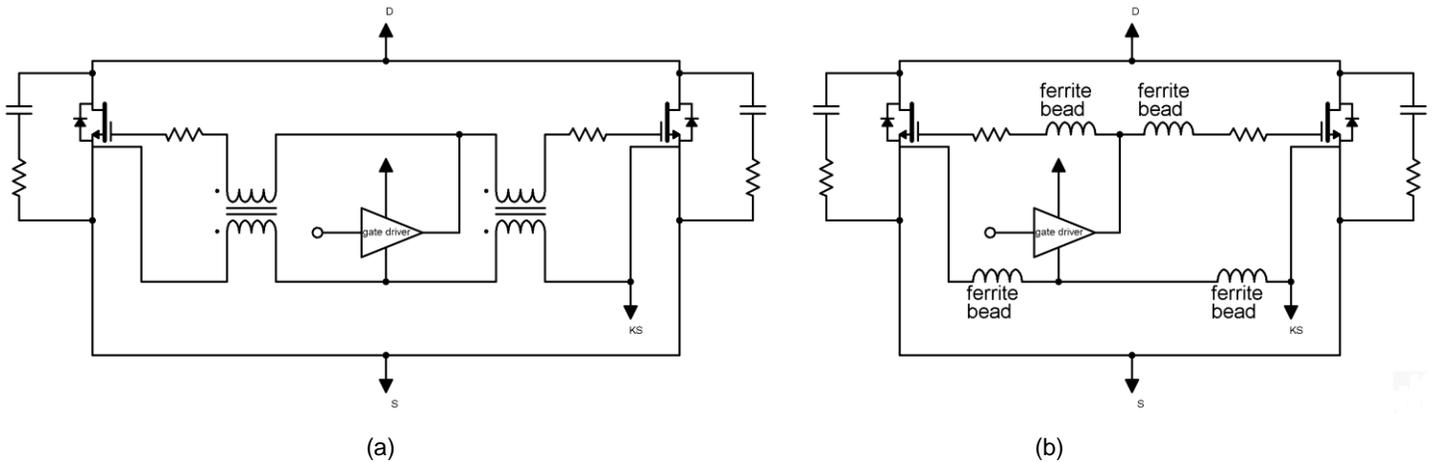


Figure 7 Recommended paralleling methods with Kelvin-source

Routing of traces can be challenging with common mode chokes. A ferrite bead on the other hand can be very small and easier to fit in a tight board layout. A ferrite bead in each Kelvin-source and gate connection works to avoid oscillation, as with a CMC. Unlike the CMC however, the ferrite beads cause a noticeable increase in delay times. Recommended impedance range is 70 to 400  $\Omega$  at 100 MHz, such as Bourns MU2029-301Y. As with the addition of CMCs, prevention of oscillations was demonstrated with a ferrite bead in both the Kelvin-source and gate connections in addition to the usual gate resistor in the gate connection.

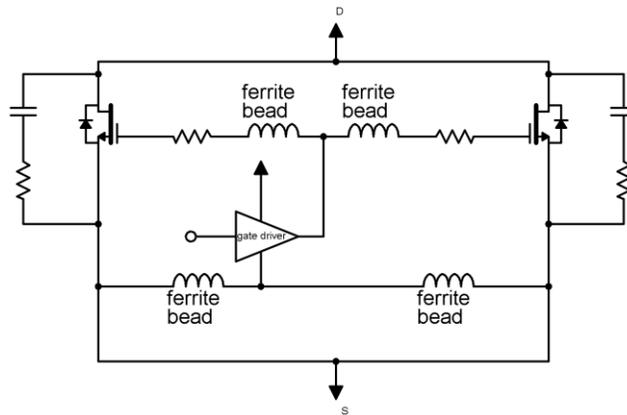


Figure 7 Recommended paralleling method without Kelvin-source

## Parts Without Kelvin-Source

Paralleling parts without a Kelvin-source pin is possible. In general, however, it is better to parallel parts *with* a Kelvin-source pin because the elimination of load current in part of the gate drive loop greatly reduces gate ringing. Without a Kelvin-source pin, the recommendation is to install a ferrite bead in both the gate and the gate drive return connection to each cascode source, as shown in Figure 7. This drawing is conceptual only. Depending on the gate driver, when using a negative turn-off voltage, the gate drive return may connect to the gate drive power supply instead of directly to the gate driver.

## Other Design Tips

As mentioned before, snubbers are usually required with cascodes, and they are especially needed when paralleling. The drain-source snubber reduces switching slew rates, making oscillation less likely to begin. See the [User Guide](#) for more information.

DC link capacitance must be close to the cascodes to minimize inductance. Surface mount ceramic capacitors next to the cascodes combined with bulk film and/or aluminum electrolytic capacitors is recommended.

Sufficient bypass capacitance near the gate driver and its power supply is necessary; insufficient capacitance here can cause oscillations. Surface mount ceramic capacitors are recommended.

Symmetrical power layout is important. High current, say greater than 100 A, with high  $di/dt$  slew rate can magnetically “push” current flowing in adjacent devices and conductors to one side, causing current imbalance and other noise related disturbances.

Gate traces *can* be long, and because we are generally not dealing with switching frequencies in the MHz range, they can be of different length without impact. Gate traces must however be shielded, preferably by a power plane on an adjacent circuit board layer. Never cross gate traces over power plane boundaries.

## Summary

Despite their high gain and switching slew rates, SiC JFET cascodes can be successfully paralleled by following the guidelines outlined in this application note. Although only two parallel parts were discussed, these paralleling guidelines apply to any number of paralleled parts. Finally, these guidelines apply not only to cascodes, but also to any other type of voltage-gated power transistor.