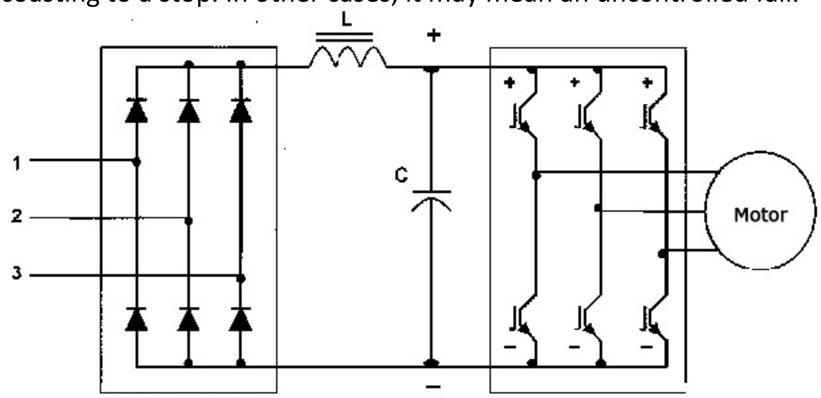
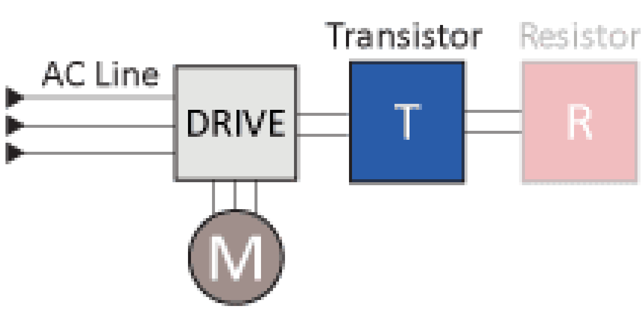
A moving mass has some quantity of kinetic energy. Like all energy, this can be neither created nor destroyed. If we want to slow a moving mass, we have to take some of its kinetic energy and move it somewhere else. A mechanical brake does this by friction, converting that energy to heat. But mechanical brakes are complex and subject to wear. A variable-frequency drive allows us to reliably convert the kinetic energy of the load into electrical energy on the drive's DC bus, slowing the mechanical load.

Unfortunately, once the energy is in the drive bus, it has nowhere to go! Standard VFDs have diode rectifier front-ends, preventing energy from flowing back to the power line. The energy can only be stored in the drive's bus capacitors, causing their voltage to rise. The drive will dissipate some of this energy internally, but only at a very low rate. If additional steps are not taken, a rapid stop will cause the drive to fault on overvoltage, causing the load to become uncontrolled. In some cases that may mean coasting to a stop. In other cases, it may mean an uncontrolled fall.



We need some way of getting energy out of the drive's DC bus. There are three basic options to achieve this.

1. **Convert the energy into heat.** This solution is by far the simplest; all we need is a resistor, and a transistor to turn it on when the bus voltage reaches a high enough level. Many VFDs have integrated braking transistors, but these are typically only rated for light duty, 20% or less. That might be good for an emergency stop, or at end of shift, but if your process requires continuous braking the internal transistor is almost certainly insufficient. In cases where heavy-duty braking is required, most drives also have DC bus terminals allowing connection of a larger external transistor. Such transistors are available in every imaginable size and duty rating.

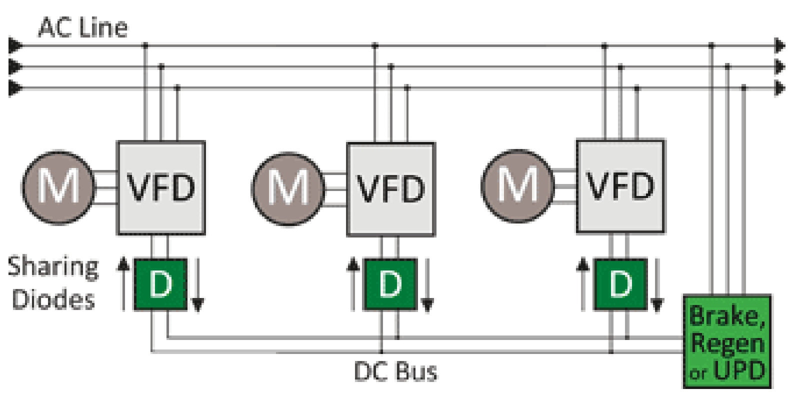


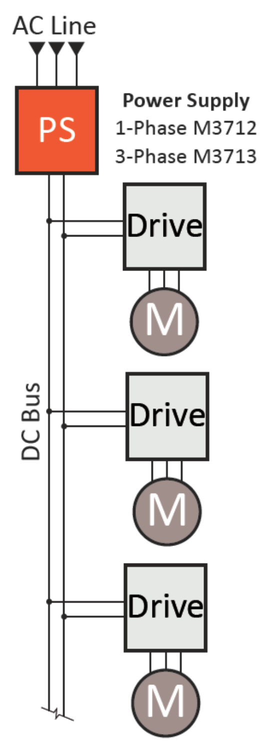
Converting braking energy to heat may be simple, but it has substantial disadvantages. For heavy-duty applications, the resistor may be several times the size of the VFD. All the braking energy is wasted, rather than being used productively to reduce the facility's electricity costs, potentially by several thousand dollars a year. If the resistor is in a temperature-controlled environment, the facility's cooling system must deal with the additional heat, which also increases costs. And in some cases, combustible dust or oil in the air can be set alight by the hot resistor, creating a fire hazard. Despite all these disadvantages, resistive braking is the default for most braking purposes, largely for reasons of cost and familiarity.

2. **Use the energy in another place.** In many installations, the braking VFD is only one of many loads on the facility's power feed. Energy can be fed from the braking VFD to these other loads, simultaneously dissipating the braking energy and reducing the facility's overall energy consumption from the grid. This energy transfer can take place either via a direct DC connection, or over the shared AC grid.

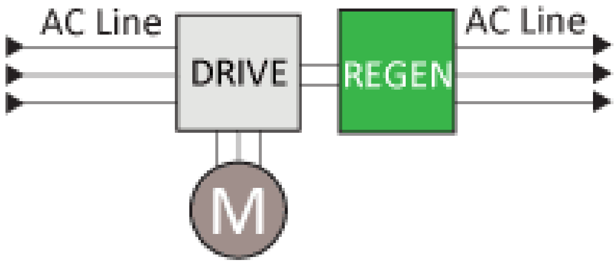
   Sharing energy between VFDs over a common DC bus can be extremely cost-effective, but has substantial limitations. First, one drive must be motoring while the other brakes, otherwise the braking energy simply drives up both drive bus voltages at once. Sharing DC between cabinets also requires expensive disconnects and fusing compared to those required by AC feeds. Because of this, common DC busses are typically limited to a single cabinet.

   Even within a single cabinet, drives can't generally be connected directly to each other, as their rectifiers will not share properly. One drive may try to source the entire common bus, resulting in overheating and catastrophic failure. Either a single external power supply is needed for the entire bus, or sharing diodes must be installed between the drives to force balancing. Despite all these limitations, in applications where it's a viable solution, common bussing can be the most cost-effective solution by far. A common DC bus can also share a single braking or backup solution among multiple drives.





   The more general solution is line regeneration, converting the braking energy to AC and sending it to other loads via their normal power inputs. Some larger VFDs are now available with an active front-end to support line regeneration, but the added cost is substantial. An external line regeneration module is typically more cost-effective, as well as being available in lower current ranges. A regen module connects to the drive's DC bus terminals, the same as an external heavy-duty braking transistor.



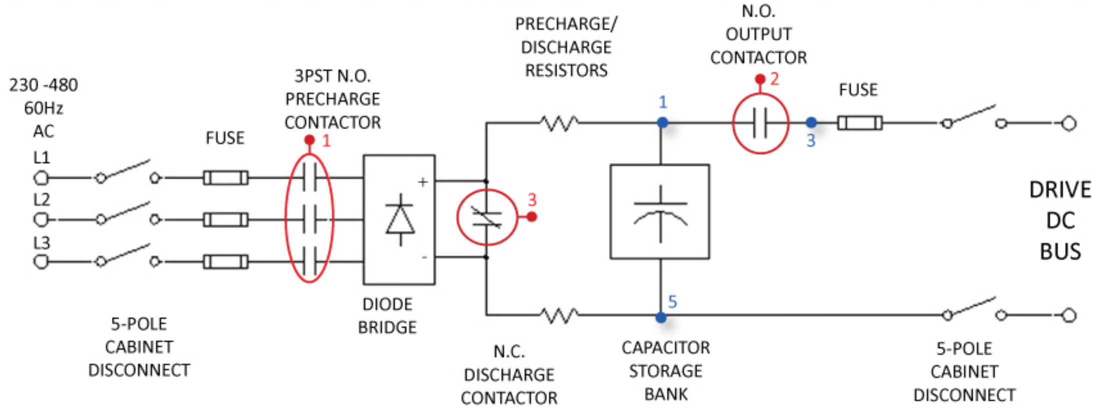
Since a line regen uses the AC grid as its load, this places some limitations on their use. Foremost, the AC line feed must be stable. If the AC line feed to the regen module is interrupted during braking, even on a scale of milliseconds, the unit will be unable to brake the VFD. It is critical that any brushes or shoes upstream of the drive and regen be completely reliable. It is also necessary that the energy being regenerated be immediately consumed elsewhere in the installation. Some utilities do not look kindly on power being pushed directly back onto the grid. In generator-fed applications, it is recommended that the total load on the generator always be at least double the power to be regenerated. Finally, most line regeneration modules do not support single-phase operation.

For heavy-duty applications, a line regen has a fraction of the footprint of an equivalent braking transistor and resistor. The initial investment in a line regen module is typically (though not always) higher than that for a resistor, but this difference is paid for over time by reduced electrical, cooling, and installation costs. For 50% duty or continuous regen applications, typical ROI for a line regen can be well under two years.

3. **Use the energy at another time.** In cases where the energy costs and additional heating of a braking resistor are not acceptable, but line regeneration is not possible, capacitive braking may be applied to great effect. This solution connects additional capacitance directly to the drive's DC bus; the greater the capacitance, the lower the voltage rise for a given braking energy. If the maximum braking energy is known, the additional capacitance can be sized appropriately to prevent drive overvoltage during a braking event. The braking energy is stored in the added capacitance, and reused during the next motoring cycle, reducing the overall draw from the power utility.

   Costs for a capacitive solution vary wildly, depending entirely on the bus voltage limitations and braking energy of the application. Because of this, most capacitive braking systems are custom designed for a specific installation. In general, the shorter the braking event, the smaller the needed capacitor bank, and the lower the installation costs. Capacitive braking is thus most appropriate for applications with continuous, rapid shifts between motoring and braking.

   All VFDs have a limit to the amount of capacitance that can be safely added directly to their bus, dictated by their internal precharge circuitry. For small additional capacitances, the internal precharge may suffice. Larger banks require an external precharge circuit. One approach is to have a resistive precharge for the bank, along with DC contactors to connect them to the drive when voltage has been equalized. Another approach is to bypass the drive's front-end and precharge circuit in favor of an external common-bus power supply. A discharger may also be desired for ease of safe maintenance.



Another factor to consider is that once a capacitor is charged to the nominal bus voltage of the drive, less than 30% of its energy capacity remains to handle braking. If it was possible to hold the capacitors at a lower voltage and only charge them during a braking event, a much smaller capacitor bank would be viable. This, however, requires the use of a bidirectional DC/DC converter. As a broad approximation, such converters only become cost-effective for braking events lasting longer than 15 seconds. Otherwise it is still more cost-effective to put a larger bank of capacitors directly across the drive bus. Direct coupling has the additional advantage of conveying a degree of immunity against power line sags and outages, comparable to the length of the braking cycle being handled.

-	Initial investment	Energy efficiency	Installation footprint	Requirements
Resistor/transistor	Low	0%	Very small to very large	Cooling for resistor
Common DC bus	Lowest	100%	Very small	Balanced motoring and braking loads, single enclosure
Line regen	Moderate	95-99%	Small	Stable AC line, sufficient grid loads
Capacitive regen	High	100%	Moderate to large	Precharge and discharge

Selecting an appropriate braking solution requires consideration of several parameters, including footprint constraints, braking profile, cost of electricity, desired return on investment, and other loads on the grid. Only when all these factors are appropriately accounted for can the best solution for an application be identified.