Guidelines and Considerations for Common Bus Connection of AC Drives

An important advantage of AC drives with a fixed DC bus is the ability to connect the buses together so that energy can be instantly transferred from one drive to another.

Whenever the normal load torque applied to a motor becomes negative (*or it is being overhauled*), the motor will act like a generator, to "regenerate" power to the DC Bus. In most common AC drives, the DC bus is supplied by a rectifier from the AC line, so there is no means for the regenerative energy to travel back to the line. When such regeneration occurs, at full load current levels, the DC bus voltage will rapidly reach an intolerably high level in just a few milliseconds. Subsequently the drive must quickly shut off to avoid being damaged by the rising voltage.

A solution to this problem is to connect the DC bus of a drive that may be in regeneration, to the bus of another drive that is outputting positive power at a rate, at least equal to, the power being regenerated by the overhauled drive. Obviously, if the motoring (*positively loaded*) drive is smaller than the drive in regen., or is lightly loaded then this scheme will not be acceptable and the combination of the two paralleled buses will rapidly rise to an "overvoltage" state.

In multi-drive systems, that continuously process material, in order to produce stretch or back tension in the material, for example, some of the drives in the system may need to be continually in regeneration. In this situation, because real work is being done to the material in the process, the sum total of the power being consumed by the whole system is positive. This means, even if there are large drives and small drives in the system, and if they are connected to a common DC bus, the combination of all motoring drives will be able to consume the energy from all the drives in regeneration. The only exception to this will be when the system undergoes rapid deceleration. For most processes such a rapid deceleration would normally be quite uncommon - most "line stops" are done with slow deceleration so as to not disrupt the tensions and accurate speed ratios between drives. With typical slow rates of deceleration, the losses in the motors, the frictional losses in the mechanics, and the work being done to the material usually represent enough positive power requirement that no net regenerative energy would be added to the common bus.

Fast System Braking

For process line applications, there occasionally is the need for a "fast line stop" or "emergency stop" which may require the whole system to deal with a net negative energy consumption.
One of the simplest ways to stop an AC drive is with DC braking. In this case DC (*or zero frequency*) is applied by the drive to the motor stator. Because there is no longer any rotational magnetic field in the motor, no AC Back EMF is produced that can be rectified by the inverter power devices which could over charge the DC bus - all of the inertial energy in the mechanical system goes into heat in the motor rotor. Naturally because the energy is dissipated in the motor this is not an appropriate stopping technique for very high inertial loads such as motors with large flywheels or winders with large diameter build up. Also the method would not be good for loads that are stopped quite often - (*something, however, that would be very uncommon for the process control system*).

The alternative to "DC injection braking", for fast line stop, is rapid decrease in frequency of all the inverters in the system. In this case considerable regenerative energy will be produced. This energy must be either removed by braking resistors or some other device, such a DC regen drive, that can transfer (*invert*) the DC energy back to the power line.

Most AC drives have available “braking transistors” that are switched in PWM mode into a power resistor at whatever switching duty cycle is needed to prevent the DC bus voltage from rising too high. In common bus applications, care must be taken in sizing the braking resistors. The braking circuitry is usually not controlled with a current limiting scheme because in a single drive application, the output inverter circuitry controls the amount of power flow in the drive. Because of this, for one drive, the power sent to a braking resistor is limited. Nevertheless in a common bus system, power can easily flow from one drive to another independent of any electronic current limit. Also the exact voltage level that one drive’s braking circuit turns on verses that of another may be slightly different. Hence it may be possible to overcurrent the braking transistor and/or resistor of a particular drive - especially where large and small drives are connected together.

The solution to this problem is proper sizing of the braking resistor. The resistance should be large enough so that when the braking transistor is continuously on (*pulse width modulation index = 1*) the resistor will only draw the maximum current rating for the drive it is connected to - i.e.:

$$\mathbf{R_{break} = V_{bus\text{-}max}/I_{max}}$$

where: $\mathbf{V_{bus\text{-}max} = 780}$ ***The lowest voltage that the braking transistor turns on.***

and: $\mathbf{I_{max} = P_{drive\ max} / V_{bus\text{-}max}}$ *$P_{drive\ max}$ is the max. power in watts the drive can regenerate. I.e.: Drive Rated Power x % Regen Current Limit.*

This becomes: $\mathbf{R_{break} = V_{bus\text{-}max}^2 / P_{drive\ max} = 608400 / P_{drive\ max}}$

With this condition, if one drive in a system begins braking at a slightly lower bus voltage than others, temporarily it may be dissipating regen power from another drive. Nevertheless, by the time the current has reached near the drives rating, the voltage across the resistor will be high enough that the other drives in the system will also have their braking transistors on. In the event that the total regen current is too high for the sum of all the braking resistors in the system, the common bus voltage will rise until one drive trips out. Once one drive trips the rest will quickly follow. Nevertheless, in such a situation, with the resistor sized in this way, no one drive will have to handle current much over 100% of its rating. (*Naturally if a system’s drives would trip because of too much regen. current the deceleration would need to be adjusted to a slower rate*.)

Common DC Bus Connection

In systems with several drives, and especially systems with large and small drives connected to a common bus, fuse protection is important. With several drives connected together the stored energy can be many times the amount that could be in an individual small drive. In the situation where a transistor or other power component might ever fail, all the energy from the entire bus will try to pass though the drive that has failed, which could be very destructive. Because of this every drive should be connected to the common bus through a fast acting “rectifier” fuse. Adding a second fuse for each drive so that both the positive and negative side of each drive's bus is fused would provide further safety. This is needed to clear a fault to ground that might occur associated with any one drive.

For a typical system the fuse sizing would be found as follows. For a drive operating on a 480 V line, the DC bus current required for a 460 V motor, that has and efficiency of 88%, and a power factor of 85% is

$$I_{bus} = 1.34\ P_{Hp}$$ (derivation below**)

or from motor rated current:

$$I_{bus} = 1.06\ I_{motor}$$ (derivation below**)

Since drive current limit can typically be set as high as 150% the fuse to the common DC bus should be at least **150% I_{bus}**. On a 480 Vac system the fuses should be 700 V.

Disconnection of a Drive from the Common DC Bus

Another desirable feature in some applications, is the ability to disconnect a drive from the common DC bus in order to replace or repair a drive, or for troubleshooting while allowing the rest of the system to operate. This can be done with a properly rated two pole switch or contactor. Disconnection from the common bus is straightforward, but reconnection of some drives may not be, because of the configuration of the DC bus precharge components.

If a drive's available DC bus connection is directly to the capacitor bank, then a drive cannot be reconnected to the DC bus if the common system DC bus is charged (*the system is powered up*), since the inrush current would be extremely high, which would clear the bus fuses. If it is not felt that a simple warning sign on the a DC bus switch, indicating that the common bus must be completely discharge before the switch could be safely re-closed, then more complex circuitry will be needed.

An external precharge resistor and contactor (*with "time delay after energization"*) for each drive could be provided. Another approach would be control logic that will only allow a contactor connecting a drive to the common bus to be closed upon power up of the entire system after the system has been "powered down" for a time. This would require some sort of "off delay" timers - e.g.: pneumatic time delay after de-energization relays. Both of these methods are somewhat costly but have been used successfully in many systems. A further, rarely used alternative (*in drives that are not already designed in this way*) is to make the connection for the common bus to the drive at a point ahead of the pre-charge circuit in the drive, if this is possible - in some drives it is not. This approach may not be desirable because it necessitates a non-standard connection or modification to the drive which makes future drive replacement difficult.

Powering the Common DC Bus

In systems of only a few drives, where all the drives are the same size and type, then the internal rectifiers can be used in each drive. In this case it is necessary to connect all the AC inputs of the drives to a low impedance common AC bus so that the applied AC voltage to every drive is nearly exactly the same under load. Upon power up of the system there may be some small differences in the timing of the precharge contactors in the various drives. However this should be small enough as to not cause any difficulty. For this approach to be successful it is assumed that all the DC bus chokes in all the drives are quite close to the same value and that the typical AC power requirement is less than the sum total of the rated power output of all the drives. In a common DC bus application this would usually be the case since some of the drives would be continually operated in regeneration which supplied part of the power required by the rest of the “motoring” drives.

Typically systems are comprised of drives of various sizes and types. If it could be guaranteed that the bus chokes in each drive had exactly inversely proportional inductance and resistance to their power rating then the scheme of providing a common AC bus to all the drive could be used. This ratio of impedances cannot be expected in a typical combination of various sized drives, so for these systems another source of DC power for the common bus will be needed.

Diode Bridge Rectifier

The most inexpensive approach to supplying the common DC bus is a large full wave rectifier. Where it is not possible to connect to the common DC bus ahead of the bus choke and precharge components, in every AC drive, a precharge resistor and contactor, and an appropriate amount of inductance, all rated for the total DC current must be add between the rectifier and the common DC bus.

The rectifier is composed of six diodes. For most systems either an insulated six diode module, or for higher power levels, three dual insulated diode modules can be used. In a 480 Vac system the diodes should be rated for **1200 V blocking** voltage and have an average current rating of .**75A average for every 1 kW of drive power**. The rectifier will produce a little less than 4 watts for every 1 kW of drive power. Allowing for a **30ºC heat rise,** the heat sink the rectifier unit will be built on, must have **a thermal conductance of** 0.133W**/ºC** for every **1 kW** of drive power. Designing the heat sink for a 30 oC heat rise will generally be acceptable for operation in a 55 oC ambient. Rectifier bridges of this type are also available built up by numerous power semiconductor manufacturers, heat sink supplies and integrators. It is recommended that a diode bridge be protected by rectifier fuses.

Precharge Circuit

To charge the common DC bus, a DC contactor and resistor are needed. Alternatively three resistors in the three incoming AC line with a three pole AC contactor to bypass the resistors could be used. In any precharge configuration, an auxiliary contact on the contactor should be used as a permissive for the system (or for any drive) to run. Also any precharge contactor should be picked up as a result of power being applied to the system and after some time delay. That time should be at **least three R*C time constants** of the precharge resistor and the sum total capacitance of all the drives on the bus. It should be assumed that there is a least **100 μF** of capacitance for every **1 kW** of drive power. The resistor (or sum of resistors) should be rated for about **5 W** for every **1 kW** of drives. The value of the resistance is not too critical since the amount of energy dissipated during each precharge is independent of the resistance value. Its value should be sized for a reasonable **precharge time such as 500 ms**. **For example, for a 100 kW system:**

$$C \approx 100(100\mu F) = .01F$$

$$RC \approx 1/3(500\text{ ms}) = .167\text{ sec.}$$

$$R = 16.67\Omega \quad \textit{- Or -} \quad 15\Omega \textit{ or } 20\Omega$$

$$W = 100(5\text{ W}) = 500\text{ W}$$

Wire wound, ceramic, tubular resistors are sufficient for this purpose.

DC Common Bus Inductor

Where it is not possible to make the common DC bus connection ahead of the internal bus choke in every drive it will necessary to have a large common DC bus choke. This must be rated for the maximum DC bus current and be designed to not saturate below at least **150%** current. The inductance is needed to reduce the harmonic current content in the DC bus to a reasonable level. An appropriate value for this inductor is:

$L = 100/P_{tot\_sys}$ mH *where P_{tot_sys} is the total system power in kW*.

Using a DC Drive to Supply the Bus

DC drives can also be used to supply the common bus current. The benefit of a DC drive is that no precharge components are needed, and such a drive has current limit and trip circuitry in the event of a fault. Also the DC drive can be regenerative which can be used to remove energy from the bus during fast system deceleration. In systems with very large flywheels, for example, DC regens have been used very successfully for this purpose.

Disadvantages to using a DC drive as the DC power supply are their cost, and they can only produce a maximum of about 85% of the voltage of a six diode rectifier on the same AC line. **For regens the voltage must be restricted to approximately 75%** of that produced by a diode rectifier, and it is

usually necessary to include additional capacitance to the common bus beyond what is available in the sum of all the AC drives.
The reason for restricting the common bus voltage when using a regen. is that in regeneration it is necessary for the DC bus voltage to remain low enough so that each SCR, as it conducts a pulse of current to the line, can be commutated off by another SCR that is scheduled to turn on in the normal "firing sequence" of SCR gating. If the bus voltage becomes too high, commutation may not occur - the result will be an "inversion fault" causing very large currents to flow. It should be noted that the danger of inversion fault always exists for DC drives, when operated in the regenerative mode, if the incoming AC voltage dips or is lost, even for a very brief moment.

Unless a DC drive is used that can operate on a proportionally higher AC line (*such as 600 or 660 Vac, for example*), the restriction of DC bus voltage means that some of the available speed range or power capability of the drives is reduced. For example for a **480 +/- 10% Vac** power system the maximum DC bus voltage should be held below approximately **500 Vdc**. Given that restriction in bus voltage, **for 460 Vac motors**, in order to produce full rated torque (*and maintain a minimum volt/hertz ratio*) the maximum speed would have to be **kept below 46 Hz**. At the same time the AC drive would need to be configured to **reach "base speed" at 46 Hz**.

Alternatively the system could be built with larger drives and motors operated at reduce volt/hertz ratio. In order for a motor to reach 60 Hz, for example, and produce the same torque as that available with a drive having at least a 650 V bus, the size of the motor (*and drive*) would need to be increased by the ratio of bus voltages, i.e.: **(650/500) = 1.30.**

If, however the bus is supply by a DC drive power by 600 Vac, for example, such a drive can continuously power a DC bus at 650 Vdc which is sufficient to allow an AC drive to produce a 460 Vac output.

When DC regen drives are used as the common bus supply, the total capacitance on the bus should be at least **120 μF for every 1 kW** of drive power in the system. The reason that this is needed is to slow the rate that the common bus voltage can rise when the inverters in the system begin to regenerate power into the DC bus. At rated power, 120μF/kW of capacitance will control the rate of rise of the bus voltage to less than 12 V/ms - slow enough that the DC drive has time to respond to the rising voltage and begin regenerating power to the AC line.

As with a system with a simple rectifier supplying the DC bus, the same need exist for an appropriate amount of inductance to be included in the DC bus circuit. The value of this inductance would be the same as described previously for the diode rectifier:
$L = 100/P_{tot\_sys}$ mH, where P_{tot_sys} is in kW.

Power Dip Ride Through

Many process systems cannot tolerate loss of control of speed ratios between drives without encoring a web break or fault in the product. In such a case the common DC bus offers a reasonable way to provide power dip ride through. One method is to connect considerably more capacitance to the bus than is available in the sum total of all the drives. A much better, but more costly and complicated approach is to use batteries.

Capacitors are sufficient for short power dips. The majority of power dips last less than **500 ms**. During that time the drives can temporarily supply, usually, up to **150%** of rated motor current as the bus voltage (*and therefore the applied motor voltage*) falls.

Because the motor torque falls off proportionally to the applied voltage, the bus can only decrease to 67% or 434 V (*for a 460 V motor*) before the motor could no long hold speed against a 100% load. Naturally if the load were less than 100%, then more dip in bus voltage could be tolerated. Nevertheless at full load, for a typical bus capacitance, the energy in the bus capacitors is only enough for on the order of 8 ms. **To extend this time to 500 ms**
(*for a 480 Vac power system*) approximately **4000 μF for every 1 kW** of drive power is needed. **[found *from C = Ibus/ (∆Vbus/∆t) = 1.7A/ (1/3•650 V/.5s) ≈ .004F*]** From this it can be seen that a fairly large capacitor bank is needed for any reasonable sized system.

Batteries can easily provide several minutes of ride through time, however they require additional circuitry. A suitable battery charger is needed that provides proper "float voltage" control without overcharging the batteries. Also the ability to "cycle" the voltage is recommended. Because the steady state DC bus voltage cannot usually be guaranteed to an accurate enough value when the bus dips, a device such as an SCR must be used to connect the batteries to the bus. This in turn requires a voltage sensing and gating circuit for the SCR. A means to disconnect or turn the SCR off after the power returns is also needed. This can be accomplished with a contactor to briefly bypass the SCR on power up. The batteries must be sized so that at the instant the load is applied to them, their dip in voltage (*which is a function of time and then recovers somewhat*) is not too great. Fuses and/or a fast disconnect device to protect the batteries as well as a way to positively assure they can be disconnected for maintenance, should be provided.

** (*page 3*) The electrical power required from the DC bus (less small losses in the transistors) is equal the electrical power consumed by the AC motor:

$$P_e = Powfac * I_{motor} * V_{motor} * \sqrt{3}$$

given the efficiency of the motor, Eff:

$$P_{mech} = Eff * P_e = Eff * Powfac * I_{motor} * V_{motor} * \sqrt{3}$$

Because the bus capacitor averages the rectified AC line, the bus voltage will be approximately 93% (*ideally 3/π or 95.493% without diode and bus inductor drops*) of the peak of the line:

$$V_{bus} = .93 * \sqrt{2} * V_{line}$$

$$I_{bus} = \frac{P_e}{V_{bus}}$$

Given the above relationships the bus current can either be found by knowing the motor power or its rated AC current:

$$I_{bus} = \left[\frac{745.7}{Eff * V_{bus}} \right] * P_{mech}$$ (P_{mech} in Horsepower)

or:

$$I_{bus} = \left[\frac{Powfac * V_{motor} * \sqrt{3}}{V_{bus}} \right] * I_{motor}$$