

## Application of Line Reactors or DC Link Reactors for Variable-Frequency Drives

### Background

The tendency among VFD manufacturers is to reduce the price and size of VFDs to meet the growing demands of end-users. As a result, reactors which were an integral part of previous generation drives, are now gradually being eliminated from newer VFDs and only offered as an added option if the end-users request them. Users of VFDs, on the other hand, are not aware of all the technical reasons why the addition of reactors is not only beneficial from a power quality point of view, but also helps to protect the electronics inside the VFD by limiting the short circuit current available at the drive terminals. The purpose of this Tech Note is to explain the many benefits of reactors, either connected at the ac line side of a VFD, or in the DC link side. The recommendation is to purchase VFDs with built-in reactors or, in case of existing VFDs, to install reactors as an added option. A DC link reactor, however, is a built-in design choice by the manufacturer and cannot be added afterwards.

### Line Reactors vs. Isolation Transformers

There are several means of obtaining line reactance: discrete inductance such as a three-phase iron core, three single-phase iron or air cores; or the leakage inductance associated with isolation transformers. Table 1 summarizes the typical characteristics of different types of magnetic devices used to provide 5% line reactance for a 50-hp VFD.

**Table 1 – Comparison of characteristics for a 50 kVA, 5% line reactance**

Device Characteristics	Isolation Transformer	Type of reactor		
		One three-phase, Fe core	Three single-phase, Fe core	Three single-phase, air core
Losses, W	1260	230	190	460
Size, in <sup>3</sup>	6500	450	625	1200
Weight, lbs	470	55	78	96
Relative cost	1.00	0.34	0.45	0.61

Isolation transformers are used if voltage transformation is required. Isolation transformers are also used to provide common-mode noise attenuation, mainly in applications for VFDs with SCR front-end or DC drives. However, for VFDs with diode bridge rectifier front-end, which is the most common topology used in the industry, a three-phase iron core reactor provides the most cost-effective option for obtaining line reactance. The size of the line reactors is typically expressed as a per-cent impedance based on the drive kVA rating. For example, a 5% line reactor for a 50-kVA drive relates to the following value of inductance per phase for the 5% line reactor:

$$\begin{aligned}
 \text{Base Impedance } (Z_b) &= \frac{V_{l-l}^2}{kVA_{drive} \times 1000} \Omega \\
 &= \frac{460^2}{50 \times 1000} \\
 &= 4.232 \Omega \\
 \text{Base Inductance } (L_b) &= \frac{Z_b}{(2 \times \pi \times f) \times 1000} \text{ mH} \\
 &= \frac{4.232}{2 \times \pi \times 60 \times 1000} \\
 &= 11.22 \text{ mH} \\
 \text{5\% Line Reactor} &= 0.05 \times L_b \\
 &= 0.05 \times 11.22 \\
 &= 0.561 \text{ mH}
 \end{aligned}$$

## **Benefits of Line Reactors**

### **Minimizing Nuisance Overvoltage Trips Due To Line Transients**

Utilities have been using capacitor banks in their distribution and transmission circuits primarily for voltage support and power factor correction. Based on system and load conditions, capacitors are switched in and out of the circuit in a daily, weekly, or seasonal pattern. While this is a very old utility practice, in light of increasing sensitivity of electronic equipment, even this practice—which is primarily intended to provide customers with quality power—is now blamed for lack of power quality.

Energizing a capacitor bank creates a momentary short circuit during which energy is absorbed from the line to charge the capacitor. This is manifested in the voltage waveform as a sudden drop in voltage with a subsequent ringing effect, the magnitude and frequency of which depend on the system parameters. The typical overvoltage magnitude is between 1.2-1.6 p.u. with a ringing frequency of 400-600 Hz. Figure 1 shows a typical voltage waveform associated with a capacitor switching transient. During the transient overvoltage event, the DC bus capacitor in the VFD attempts charging to the peak of the incoming transient line voltage, resulting in the VFD tripping off-line – showing an overvoltage fault code or in some cases even damaging the input diode front-end. Typically these overvoltage trips will happen at about the same time of day, usually in the early morning when capacitors are switched in response to the load demand. For some VFDs, overvoltage trips will be correlated with switching of large motor loads and power factor correction capacitors within the facility. Smaller size VFDs and VFDs that are lightly loaded are more susceptible to overvoltage trip caused by capacitor switching transients.

Reactors provide two main functions that help minimize the effect of capacitor switching transients on VFDs: First, the reactor impedance provides a voltage drop that reduces the dc bus voltage, thereby providing a greater margin for overvoltage trip. Further, reactors limit the magnitude and the rate of the surge current charging the capacitor. The required reactor size is a function of the transient magnitude, impedance of the source and drive trip level. Field experience indicates that in most cases a 3% reactor based on the drive kVA rating is usually sufficient. For some cases, typically when the overvoltage transient is greater than 1.6 p.u., a 5% reactance may be required. If the voltage transient occurs when a VFD is idling, then even a line reactor may not solve the problem, especially for smaller VFDs rated less than 5 hp. This is because while idling, the VFD does not draw any line current and, furthermore, the excess energy on the line side cannot be transferred to the connected motor load. Surge-protective devices (SPDs) are often misapplied in an attempt to prevent these overvoltage trips and to protect VFD input diodes. Typically, SPDs have a much higher clamping voltage than switching transients. In some cases where the SPD is unadvisedly selected with a low clamping voltage, it can become the point of failure due to insufficient energy-handling capability.

### **Reducing Input Line Current Harmonics from VFDs**

The input current waveform of VFDs with diode bridge rectifier is characterized by a two-pulse current waveshape in each half cycle, each pulse related to the charging of the DC bus capacitor to the peak incoming voltage. The result is a non-sinusoidal current flow with a total harmonic distortion (THD) of typically 90-150% with a harmonic content that is predominantly 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup>, and 13<sup>th</sup> harmonics. The application of a line reactor or a DC link reactor causes the discontinuous current to become continuous. The main reason is that with reactors, the voltage at the VFD terminals becomes flat-topped, and the charging time for the DC bus capacitor increases, thereby increasing the current pulse width while decreasing its peak amplitude. Figure 2 shows the line current for a 100-kW VFD with and without a 3% line reactor.

### **Improving VFD Power Factor and Reducing Line Losses with Reactors**

Use of line reactors as explained in the preceding section reduces harmonic currents. Reducing harmonic currents reduces the total rms current which is defined as the square root of sum squares of all harmonic frequencies including fundamental. Reducing the total rms current causes a reduction of the kVA demand of the drive. In turn, reducing the kVA demand reduces the line losses within the customer premises, which can pay for the reactor in short time. Since the line reactor does not change the fundamental component of the current, the kW input required still remains the same, dictated by load requirements. This means that the ratio of kW/kVA improves and this ratio is the definition of “true power factor.” It is extremely important to keep in mind that VFDs typically have a poor power factor (0.6-0.65). However, this does not mean that VFDs have a high reactive power demand. VFDs do not have any reactive power demand as the reactive power is supplied from the DC bus capacitor. The high kVA demand from VFDs, which related to poor factor is due to the harmonic content in the current waveshape; reducing the harmonics either by a reactor or by an

appropriate harmonic filter leads to an improvement of the power factor. Figure 3 shows the benefits obtained by adding a 3% line reactor toward improving power factor, reducing rms line current, reducing kVA demand, and reducing harmonics.

### **Minimizing Line-Side Fuse Operation During Unsymmetrical Voltage Sags**

The large majority of faults on a utility system are single line-to-ground faults. During such a fault, the voltage at the drive terminals has a high degree of unbalance. This momentary unbalance in the supply voltage causes high current on one of the phases on the line side of the VFD (Figure 4). The current peak magnitudes depend on the stiffness (available short-circuit current) of the source.

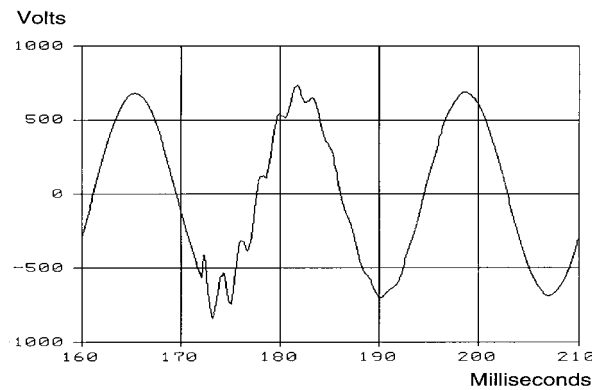
For VFDs that are connected close to a transformer allowing a high available short-circuit current, the peak current may reach 200% to 250% of the rated line current, causing operation of the line-side fuse during the sag. Application of line reactors reduces the available fault current at the drive terminals and minimizes the chance of fuse operation during unsymmetrical voltage sags.

### **Conclusions**

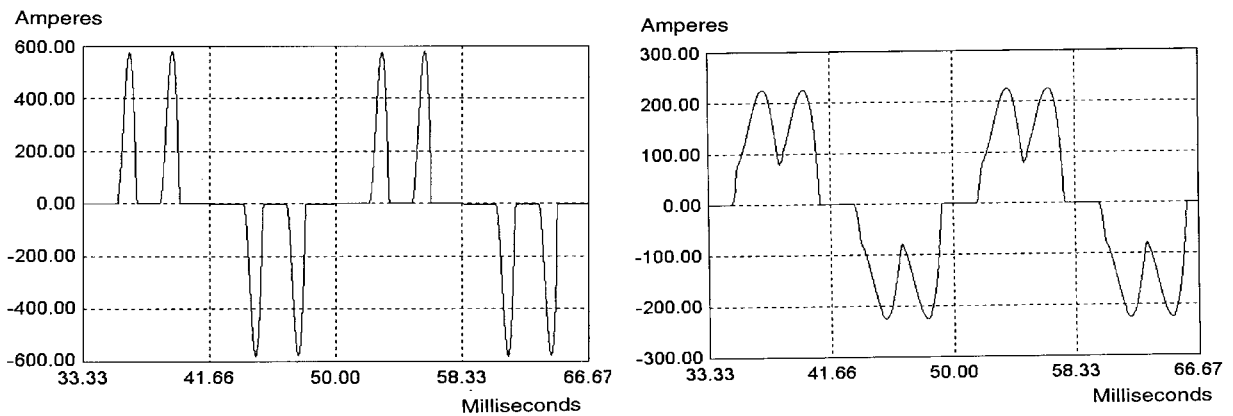
Benefits of line reactors include the following:

- Minimize nuisance overvoltage trips of VFDs due to line transients;
- Protect drive input diode front-end by reducing available fault current;
- Reduce the harmonic current distortion, while increasing the power factor of the load;
- Minimize line side fuse operation during momentary voltage unbalances.

Considering the cost-to-benefit ratio, the price (typically between \$6-\$25/hp depending upon the size) justifies the specification of reactors, even if capacitor switching transients are not a concern.



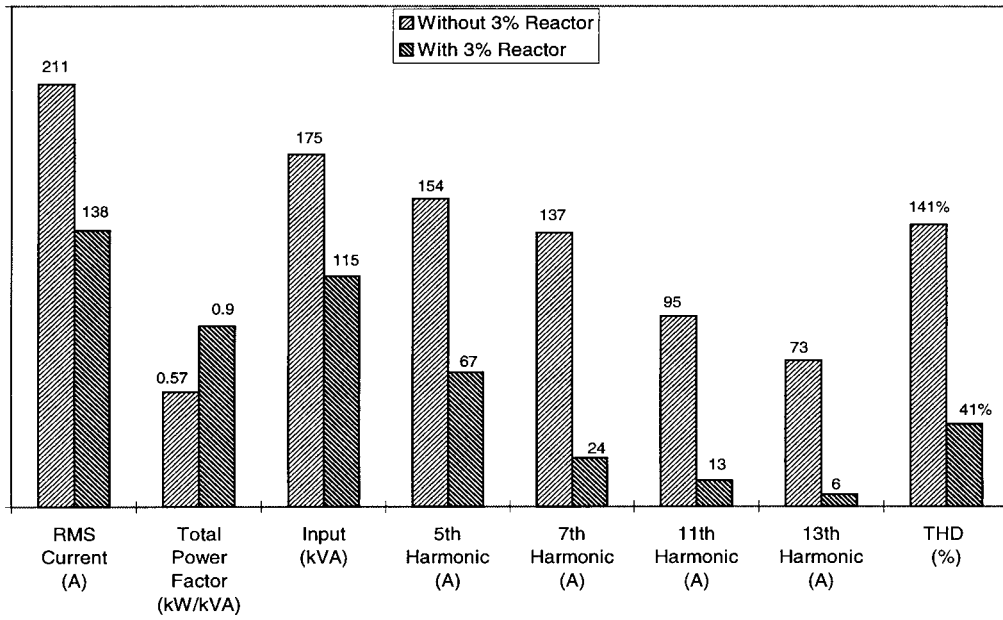
**Figure 1 – Typical waveform of capacitor switching transient**



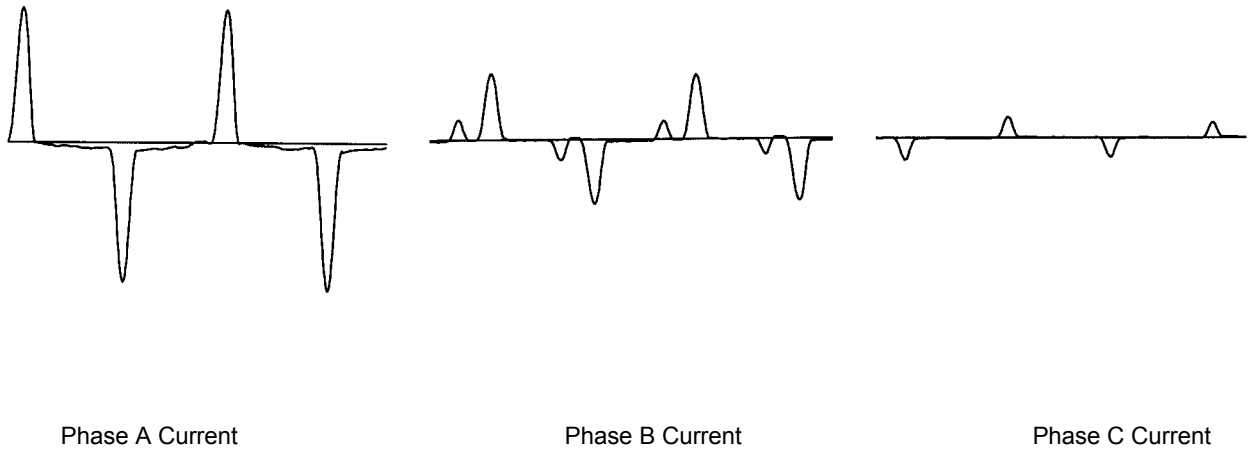
(a) No Line Reactance

(b) With 3% Line Reactance

**Figure 2 - Effect of line reactance on the input current waveform**



**Figure 3 – Performance of a 100-kW VFD without and with a 3% reactor**



**Figure 4 – Effect of phase unbalance on line current waveforms**