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Application Note

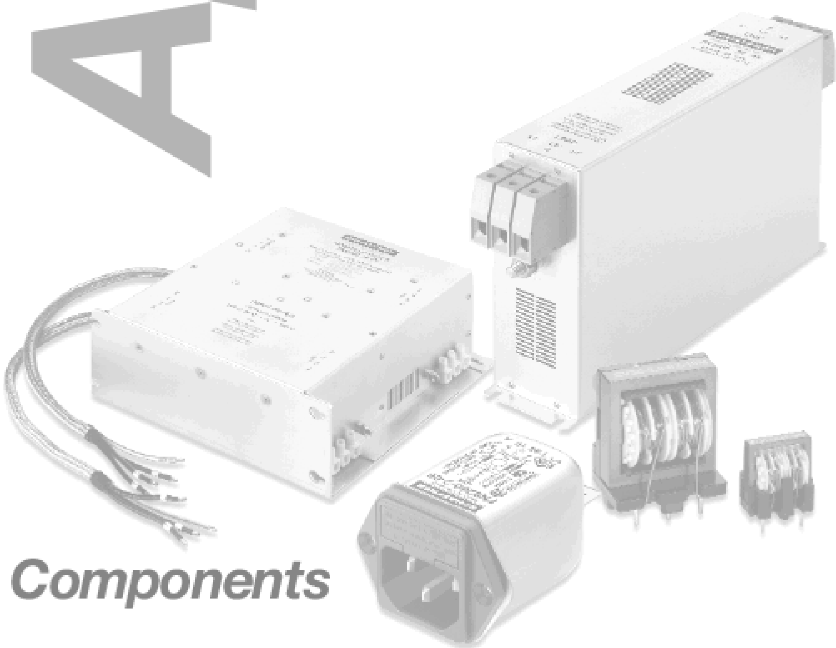
APPLICATION

OF

LINE REACTORS

IN

POWER ELECTRONICS



Components

SCHAFFNER EMV AG, COMPONENTS DIVISION, CH-4542 LUTERBACH, SWITZERLAND, www.schaffner.com

Application of Line Reactors in Power Electronics

Stefan Melly, Product Marketing, August 2003

Tim Williams, Elmac Services, August 2003

Line reactors are a formidable weapon in the power system builder's armoury. These components are used in motor drive and other applications, to reduce harmonics and commutation notches, to increase drive system reliability and up-time, and to protect both the equipment and the mains against low-frequency interference phenomena. This application note covers the specification and use of such reactors and discusses the benefits they bring to the system builder and operator.

1 Introduction

This application note introduces Schaffner's range of line reactors and discusses the advantages they offer system builders in many power control and use situations. Power quality is an issue of increasing importance and many electricity supply utilities are now mandated to provide a mains supply with controlled quality parameters such as harmonic distortion and voltage limits. To achieve this they must in turn place restrictions on the pollution caused by various types of connected load, especially those which draw distorted current waveforms. One straightforward way of meeting these restrictions, and at the same time protecting the load itself from incoming low-frequency disturbances, is to place a line reactor on the supply input.

Schaffner are well known for their ranges of EMI filters which can also be located at the input of many loads which create RF interference (RFI / EMI). Line reactors are complementary to these filters and it is now possible to obtain all these power input components from a single source, or even as a single component comprising EMC-filter and line reactor.

2 What is a line reactor?

The term “line reactor“ is fairly loosely applied to any inductive component that is used in a power line application. In fact such components can be used for several purposes, not limited to the power input of a product or system, and the variety of applications is addressed later. The line reactors discussed in this application note are designed as follows:

2.1 Construction

Schaffner's range of three-phase line reactors (RWK 212, RWK 213 and RWK 312) are built with laminated iron cores, very similar to the construction of power transformers. Connections are via terminal blocks or screw lugs for the lower power types, and by copper bar for higher power. The reactors are designed in an open-frame design without housing, which is the most common and cost effective way for the most diverse power applications. In order to reduce humming noises, all line reactor coils are treated with a special impregnant.

Picture 1: RWK 212 line reactor from Schaffner

2.2 Specifications

The components are specified for current rating and inductance. The two most common inductance ratings for power drive systems are 4% u_k and 2% u_k. The u_k rating is sometimes called the “short circuit voltage drop” (relating to transformer practice) and sometimes simply the “percent impedance”. It is understood to be the voltage drop across the reactor at nominal current and supply frequency, expressed as a percentage of supply voltage. In European applications, the three phase supply voltage is 400V and the frequency is 50Hz. If the load is drawing exactly the same current as the reactor’s nominal rating, then the figure of 2% or 4% can also be regarded as a percentage of the load impedance.

The voltage drop is due both to resistive and inductive parts of the total impedance, but the unit is designed so that the inductive part dominates and therefore the voltage drop can be directly related to the inductance at 50Hz.

Example:

For instance, a Schaffner 60A 4% reactor has an inductance of 0.49 mH. At 50Hz this is an impedance of 0.154 ohms, which at 60A drops a voltage of 9.2V. For a 400V three phase supply this is a percentage level of ($\sqrt{3} \cdot 9.2/400$) = 4%.

This is the reactive voltage drop which occurs at the supply frequency and does not represent a loss of power. The only power loss is the dissipation in the resistive component of the winding and core.

2.3 The effect of inductance

To fully understand the benefit of an inductive component we have to appreciate the impact it has on a power circuit. Whenever the current passing through an inductor changes it develops a voltage across its terminals according to the equation:

$$V = -L \cdot di/dt$$

Thus if the voltage available in the circuit is limited, so also is the di/dt. Alternatively, if the circuit load or supply characteristics are such as to create a voltage step then the inductor limits the di/dt this causes.

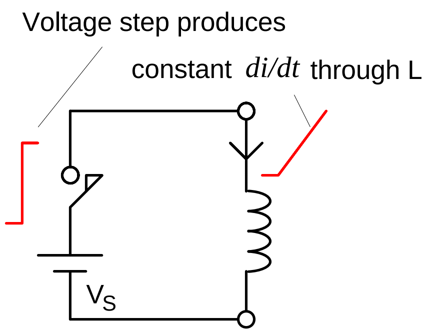


Figure 1: inductive characteristics

3 Applications in Variable Speed Drives (VSD)

One of the most common application areas for line reactors is in variable speed electrical power drives (VSDs). Such systems occur in ratings from less than 1kW to more than 100kW and are popular because of the power efficiency and controllability that they bring. This application note concentrates on the use of reactors in such systems, although other power applications can benefit equally.

3.1 The need for protection

VSD manufacturers nowadays are operating in an extremely competitive marketplace and the tendency is to offer drive products without input reactors unless the end user specifically requests it. Users, though, often are not familiar with the reasons why a reactor is beneficial both for the reliability of the drive's electronics and also for the quality of the power supply. The aspects which are affected by introduction of an input reactor are:

- buffering the electronics from input transients due to utility and load switching elsewhere in the supply
- preventing high inrush currents and reducing the transient load on the input components
- improving VSD crest factor and consequently reducing power input line losses
- controlling emissions of line current harmonics due to the rectifier input circuit
- controlling the impact of commutation notches on the power supply
- protecting and increasing the service life of dc-link capacitors of VSDs
- reducing differential mode low-frequency phenomena up to a few hundred kHz

Each of these areas is discussed in the following sections.

3.2 Overview of uses

Reactors and filters can be used in various locations in a power drive system: in line with the power input (line reactor), in the DC link between the rectifier and capacitor (dc-link choke), and at the drive output to the motor (motor reactor). A reactor at each of these positions has particular effects, not by any means mutually exclusive. Generally it would be unnecessary to have a reactor in both the power input and the DC link, but the functions of the input line reactor are quite different from a filter at the drive output, and it is entirely reasonable to include both of these.

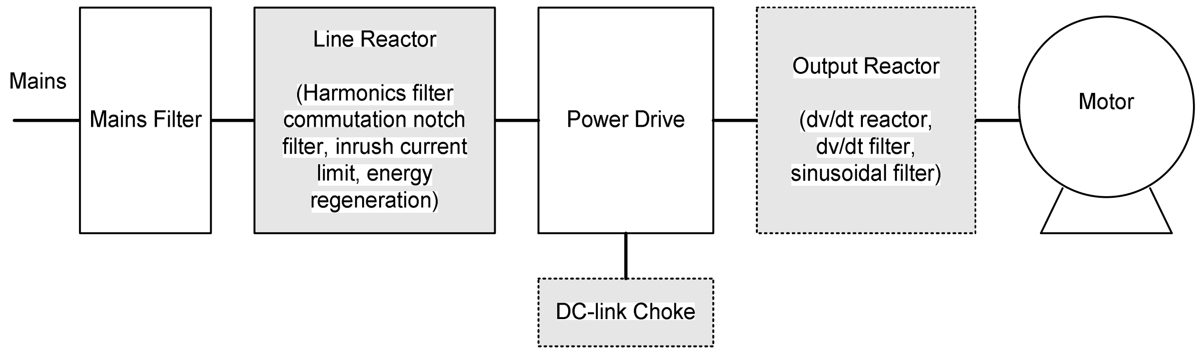


Figure 2: Positions in a drive system where reactors can be used

3.3 Line input

A reactor in the power supply input will do two things: protect the drive electronics from power disturbances, and protect the power supply from disturbances created by the drive.

3.3.1 Harmonic attenuation

A three-phase input rectifier with a reservoir capacitor draws current discontinuously. When the input voltage across any pair of diodes is greater than the DC link voltage, maintained across the capacitor, then current flows and charges the capacitor. When the input voltage is less, the diodes block the input current and the reservoir capacitor supplies the DC link current. This gives rise to a characteristic “double pulse” input current drawn from any of the three phases; these sum in the DC link to give a series of unipolar pulses of current at six times the frequency of the input (300Hz in EU applications).

Conditions:

Supply voltage: 400V

Supply source impedance: 0.15Ω

Reservoir capacitance: 2500µF

Load impedance and power: 20Ω / 14.94kW

The graph shows the rectified input current drawn when the supply voltage exceeds the DC link voltage

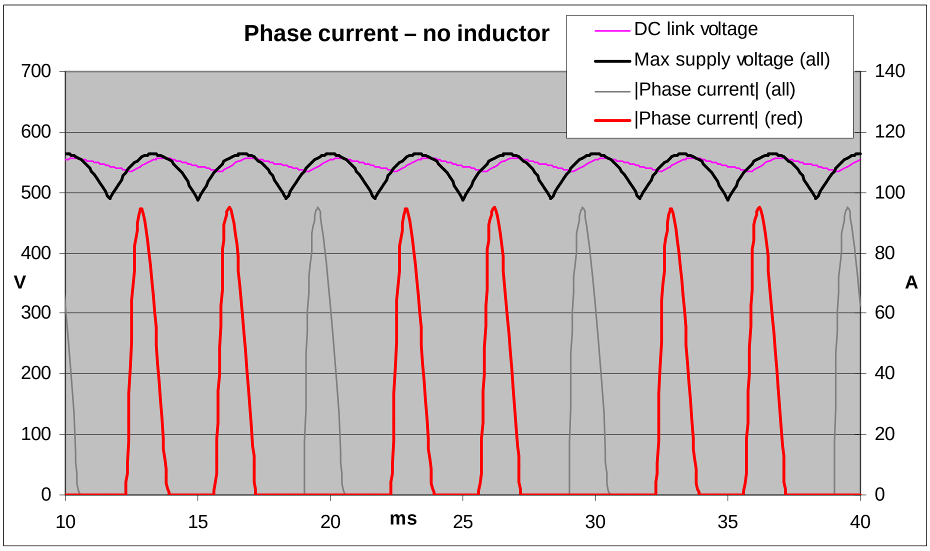


Figure 3: Input pulses in a 3-phase rectifier circuit (six-pulse)

The discontinuous phase current is rich in harmonics of 50Hz. The total harmonic distortion (THD) is typically 90-150% with a harmonic content predominantly made up of 5^{th}, 7^{th}, 11^{th} and 17^{th} harmonics.

The effects of these harmonics on the power supply and via this on other users are manifold:

- transformer and neutral conductor overload due to excessive zero-phase currents
- overheating of power factor correction capacitors due to high frequency currents
- conductor losses due to skin effect at higher frequencies
- voltage distortion, amplified at remote points in the network due to resonances
- failure of direct-off-line induction motors, trying to run at harmonic frequencies
- acoustic and electrical interference at audio frequencies
- increased earth leakage currents due to stray and EMI filter capacitances

The electricity supply industry is naturally keen to reduce these effects – it is, in Europe at least, mandated to offer a supply of guaranteed quality, and it can only do this if the user’s pollution is controlled. Limits are placed on harmonics emissions either by the terms of connection offered by the utility, or by a requirement to meet international standards, of which IEC61000-3-2 for equipment < 16A per phase and IEC61000-3-12 (draft) for equipment current between 16 and 75A per phase, are the most significant. In the USA, harmonics are in the scope of the IEEE519 standard.

To meet these requirements for a standard three-phase rectifier-reservoir input circuit, some inductance in line is needed. This is the function of the line reactor. The reactor's inductance slows the rate of rise of each individually rectified pulse and continues supplying current for a millisecond or two after the input voltage has dropped below the DC link voltage. Thus the six-pulse waveform is "stretched" and can become continuous rather than discontinuous if the inductance is high enough.

Conditions:

Supply voltage: 400V

Supply source impedance: 0.15Ω

Reservoir capacitance: 2500µF

Load impedance and power: 20Ω / 14.28kW

Line reactor: 0.84mH

The graph shows the rectified input current drawn through the line reactor – same scale as figure 4

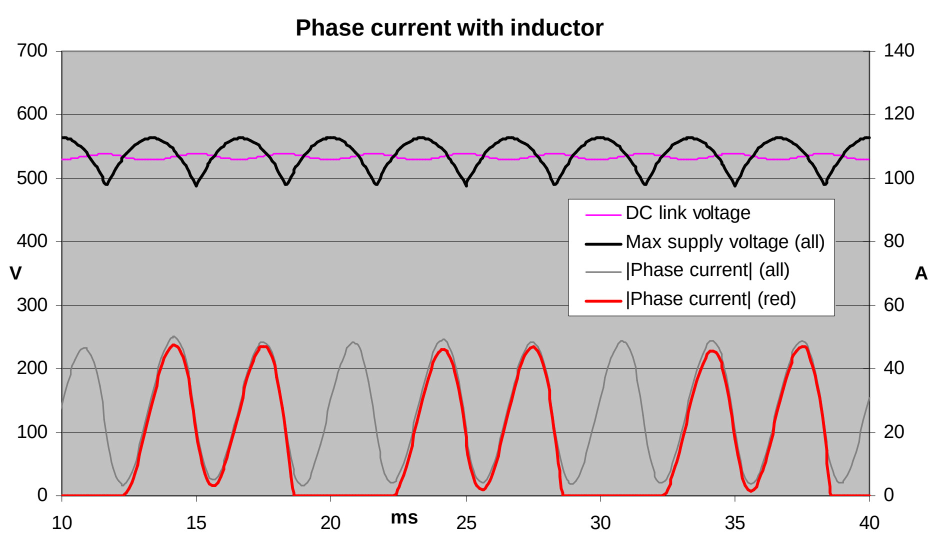


Figure 4: Rectified input current with a line reactor

At the same time the peak amplitude of the current is reduced. This means that the crest factor of the waveform is reduced so that the peak-to-rms ratio is lower. This has many benefits, including lower stress on the reservoir capacitors and hence greater reliability.

The harmonic attenuation is directly related to the value of inductance in circuit. Since Schaffner reactors are specified as a percentage voltage drop, we can relate this percentage to the harmonic attenuation as in table 1. As can be seen, the 4% inductor gives considerably better harmonic attenuation than the 2% but at the cost of greater voltage drop and a much larger component.

Harmonic number	INPUT IMPEDANCE (u_k) vs. REMAINING HARMONICS (%)										
	0.5%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
5th	80	60	46	40	34	32	30	28	26	24	23
7th	60	37	22	16	13	12	11	10	9	8.3	7.5
11th	18	12	9	7.3	6.3	5.8	5.2	5	4.3	4.2	4
13th	10	7.5	5.8	4.9	4.2	3.9	3.6	3.3	3.15	3	2.8
17th	7.3	5.2	3.6	3	2.4	2.2	2.1	0.9	0.7	0.5	0.4
19th	6	4.2	2.8	2.2	2	0.8	0.7	0.4	0.3	0.25	0.2
% THD-I	102.5	72.2	52.3	44.13	37.31	34.96	32.65	30.35	28.04	25.92	24.68

Table 1: Harmonic attenuation versus reactor specification

The decision for higher or lower reactor impedance is always up to the requirements of a particular application, its degree of needed harmonic reduction and the maximum acceptable voltage drop at the mains input.

3.3.2 Commutation notches

Certain types of VSDs (e.g. current converters) have a particularly aggressive effect on the power supply. In commutating converters load current is switched from one branch to its opposite under control of the drive electronics. At the moment of transfer all switches are on briefly (Figure 5) and there is therefore a transient short circuit across the supply. The current that flows at this instant is limited only by the switch resistance and the source impedance of the power supply, not by the load.

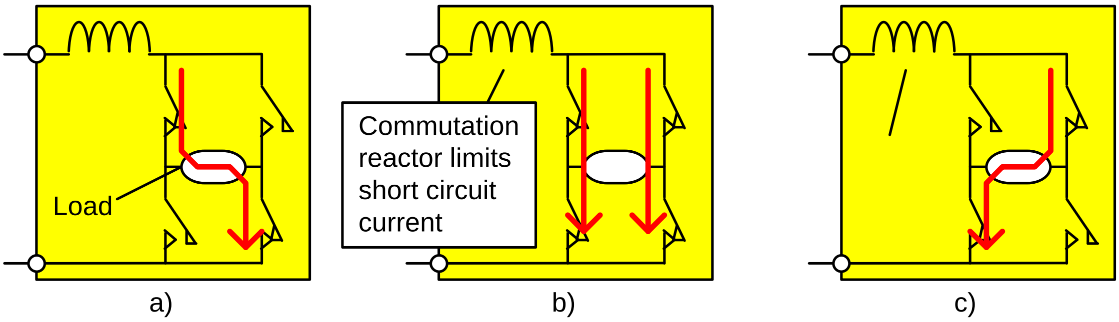


Figure 5: Event of commutation

To protect the switches, some reactance in the supply circuit is essential and this is the function of the commutation reactor, which is provided as part of the system. But the commutation reactor is not designed to protect the supply itself. If the supply source impedance is a significant fraction of that of the commutation reactor, then the short circuit current causes "commutation notches" in the supply voltage, the depth of these notches depending on the ratio of the supply source impedance to the commutation reactor impedance, assuming the switches present a short circuit.

While these notches do not seriously affect the operation of the converter – after all, they are caused by it – they can be fatal to other apparatus connected to the same supply. It is possible, for instance, for the notches to cause a false zero crossing (Figure 6).

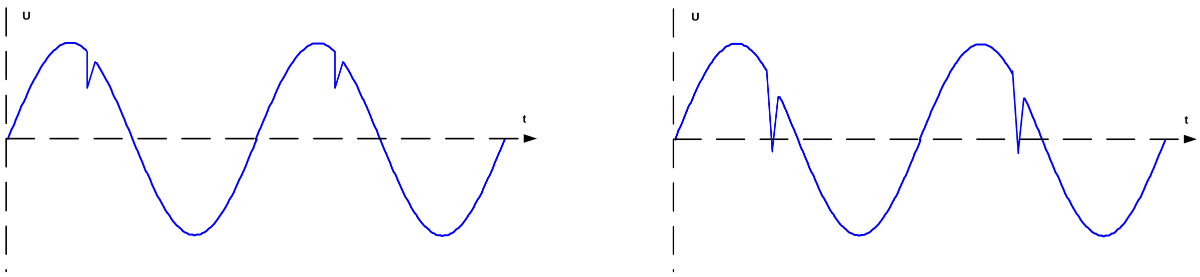


Figure 6: Examples of commutation notches

Thus in this case the purpose of the line reactor is to be applied in series with the power input, to protect the power supply and reduce the amplitude of the notches on the supply connections. The notch amplitude is now a function of the supply impedance and the total inductance (line and commutation reactors), as well as the commutation period:

Notch depth % = $Z_C / (Z_C + Z_D)$

where :

Z_C is the supply network impedance at the point of connection (assumed reactive), and

Z_D is the decoupling reactance between the point of connection and the converter terminals (line plus commutation reactor)

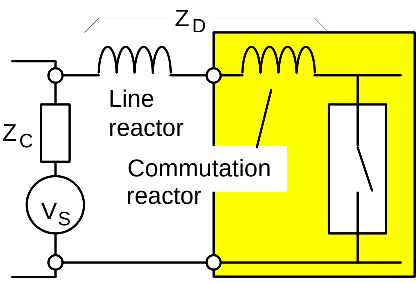


Figure 7: adding a line reactor

As a secondary effect, the short circuit current is reduced as the line reactor augments the effect of the commutation reactor, so the switches and other components will enjoy increased reliability.

EN 61800-3, the harmonised EMC standard for adjustable speed drive systems, recommends a maximum notch depth of 20% for the domestic environment and 40% for other environments, and says (see its annex B.1)

Where notches are to be considered, the manufacturer shall provide the following information to the user:

- *value of any decoupling reactance's which are included in the power drive system;*
- *available decoupling reactance's which can be externally added for mitigation.*

3.3.3 Rectifier and capacitor protection

When the power is first applied to an un-powered device, the DC link capacitor is discharged. Unless power is applied at the zero crossing or a soft start circuit is used, an instantaneous high current will flow for a few milliseconds while the capacitor charges. This inrush current is limited only by the supply impedance and will normally be many times the rectifier's steady state AC current rating. A rectifier is normally specified to withstand a transient inrush current (for instance a 40A 40HF80 is specified to 570A I_{FSM}) but unless there is extra impedance in the line, some faith is needed that this transient rating won't be exceeded.

A line reactor, among its other virtues, provides this impedance. As an example, say power is switched on near the peak of a 400V waveform with a 0.84mH RWK 212-35-KL (35A 4%) unit in line. Then the initial di/dt is V/L = 565/0.84 = 673 A/ms and the peak current is limited to about 600A (see Figure 8). Without this impedance, and if the total supply impedance is, say, 0.2Ω, then the peak current at turn on can be over 2000A for a few tens of microseconds. Because the inductor carries on supplying current after the peak of the supply voltage, the DC link voltage can exceed the normally expected peak voltage by an amount determined by the ratio of inductance and reservoir capacitance.

Conditions:

Supply Z_S 0.2W

DC link capacitor 1000µF

Load 20W

Inductor 0.84mH

(only one phase shown for clarity)

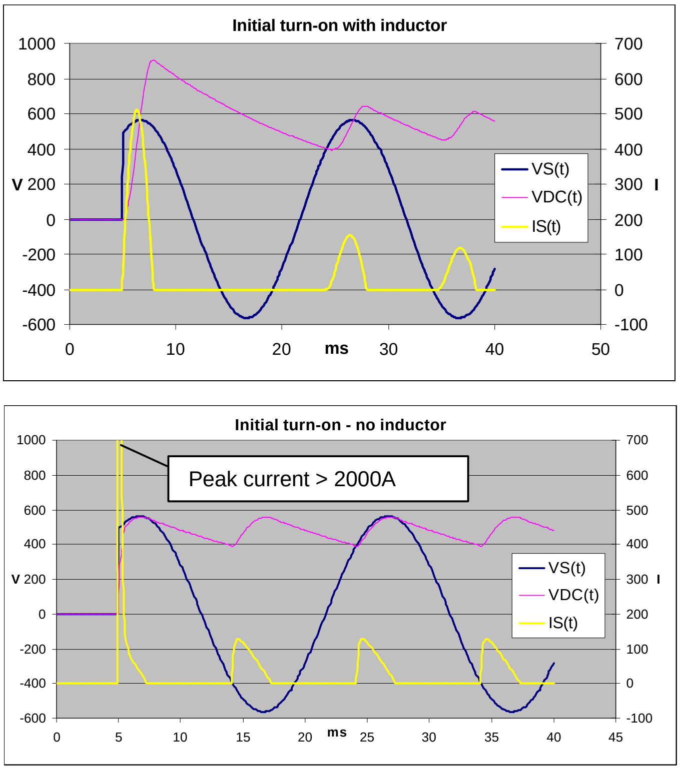


Figure 8: Inrush current limiting with a line reactor

3.3.4 Nuisance tripping

Inrush current is not the only thing a line reactor controls: it will also dramatically reduce the amplitude of transient surges on the supply. This can be due to fault or lightning surges, or more commonly due to capacitor switching. Utilities use capacitor banks in their distribution and transmission circuits primarily for voltage support and power factor correction. Depending on load conditions, capacitors are switched in and out of the circuit in a daily, weekly, or seasonal pattern.

But switching in a capacitor bank creates a momentary short circuit during which energy is absorbed from the line while the capacitors charge. This appears 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 to 1.6 times the nominal with a ringing frequency of 400 to 600Hz. During the transient overvoltage event, the reservoir capacitor in the VSD tries to charge to the peak of the incoming transient line voltage, resulting in the VSD tripping off-line – showing an overvoltage fault or in some cases even damaging the input rectifiers. 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 VSDs, overvoltage trips will be correlated with switching of large motor loads and power factor correction capacitors within the same plant. Smaller size VSDs and VSDs that are lightly loaded are more susceptible to overvoltage trip caused by capacitor switching transients.

Reactors reduce the effect of capacitor switching transients on VSDs in two ways. Firstly, the reactor impedance provides a voltage drop that reduces the DC link voltage, thereby providing a greater margin for overvoltage trip. Secondly, a reactor limits the magnitude and rate of the surge current charging the capacitor.

In most cases a 4% reactor is sufficient, but if the voltage transient occurs when a VSD is idling, then even a line reactor may not solve the problem, especially for smaller VSDs rated less than 5 hp. While idling, the VSD draws little line current and the excess energy on the line side cannot be transferred to the connected motor load. Surge-protective devices (SPDs) may be tried in an attempt to prevent these overvoltage trips and to protect VSD input rectifiers, but these have a much higher clamping voltage than switching transients. If one is wrongly selected with a clamping voltage that is too low, it can be a weak point due to insufficient energy-handling capability.

3.4 DC Link

Many of the virtues of a reactor in line externally with the power input are also gained if the reactor is placed in series with the DC link. This position also reduces the harmonic emission, controls inrush current and reduces nuisance tripping due to capacitor switching overvoltages. It does not though protect the input rectifiers from incoming transient overvoltage surges.

A DC link reactor needs only two windings, compared to three for a three-phase line reactor. However these windings must be rated for a higher current and therefore for a given reactor size, there is no gain, since the inductance value must be realised with a larger winding. If a VSD is already supplied with an adequate DC link reactor then there is little merit in adding a line reactor, but if the VSD has no DC link reactor then a line reactor is more easily added externally to the power supply terminals.

3.5 Motor output

Although this application note is focussing mainly on the application of line reactors, a brief overview on the benefits of output reactors will be given in the following as well (more details on Schaffner output reactor and output filter solutions can be obtained by any Schaffner sales point upon request).

VSDs intentionally chop the waveform that is applied to the motor and this creates a drive spectrum which is rich in harmonics, just as it does at the power input. Problems are caused for the motor as a result. These problems are addressed by the various Schaffner output filter ranges.

3.5.1 Motor stress

The high switching speed of modern semiconductors gives good thermal efficiency in the drive but it results in intense dv/dt transitions on the output to the motor. These cause severe EMI which can be dealt with by careful use of screened cables, at considerable expense, but they also affect the motor directly. The steep edges combined with the cable parameters cause brief overvoltage spikes on each transition which severely stress the motor winding insulation. At the same time, the harmonics created by the switching action give additional magnetic losses in the motor, so it runs hotter for a given power. Typical motor insulation, already stressed by the spikes, has a lifetime that halves for every 10°C rise in temperature.

A further problem is that the high frequency currents caused by the dv/dt transitions are coupled by stray capacitance to the motor frame and can pass through the bearings, effectively overheating and destroying their lubricant.

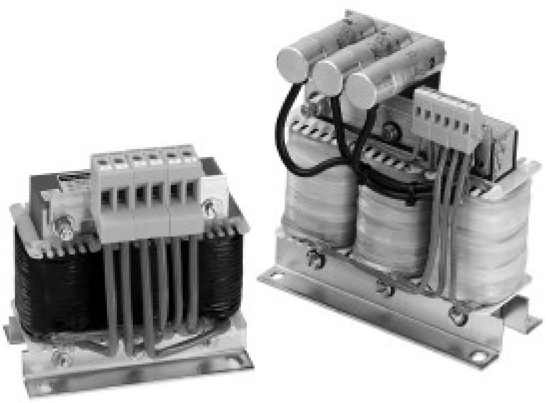
Taking all these issues together, a motor which is coupled directly to the output of a high efficiency VSD can expect a much reduced service life. All of the problems are addressed by including an output filter or reactor which attenuates the output dv/dt.

3.5.2 Motor noise

Because the carrier frequency and harmonic spectrum of many drives is in the audible range we can actually hear the higher frequencies in motors which are being operated by these drives. (Travel on any modern electric railway train to confirm this.) An output filter or reactor installed on the drive output will virtually eliminate the higher order harmonics (11^{th} and up) and will substantially reduce the lower orders (5^{th} and 7^{th}). By reducing these harmonics the audible noise is diminished, typically by 3 to 6dB.

3.5.3 Short circuit protection

When a short circuit occurs at the motor, very often the VSD transistors are damaged. Although VSDs will have over-current protection built in, the short circuit current can be severe and its rise time so rapid that damage occurs before the protection circuitry can react. A reactor or output filter will limit the current to safer values and will slow down the short circuit current rise time. The drive has longer to shut down the system, and although the motor still has to be repaired, the drive transistors are safe.



Picture 2: RWK 212 line reactor and FN 5010 sinusoidal output filter from Schaffner

4 Other applications

The above discussion has concentrated on variable frequency drives, but many other applications in the power industry can be found for line reactors. These can include power supplies (switched mode and UPS converters), lighting control systems, rectifiers, welding equipment, electric arc furnaces, machine tools, spark erosion machines and so on. Anywhere that a load di/dt or dv/dt can feed back to the point of connection and cause pollution or reliability problems, a line reactor can help.

4.1 Can a line reactor help RF emissions?

It might be thought that since the line reactor provides inductance, it will effectively block RF emissions as well as supply harmonics. In the lower RF frequency range, up to a few hundred kHz, this does indeed happen for the differential mode noise. But because it is optimised for the lower frequencies, it has a relatively high self capacitance and this diminishes its effectiveness at RF. A line reactor cannot by itself be relied on to control RF emissions across the whole range up to 30MHz, and an EMI suppression filter is still necessary.

Using a line reactor does have a less obvious advantage, though. An EMI filter should always be sized for the peak AC current flowing in the line, not the RMS current. As we have seen, a reactor reduces this peak current, which allows a smaller EMI filter to be chosen. Also, the differential mode capability of the filter is limited at the bottom end of the range. Inserting a line reactor significantly augments this capability, again allowing a smaller filter to be specified while gaining better performance.

Schaffner FN 3400 range offers both. By having a line reactor and an EMI filter situated next to each other within the same housing, FN 3400 takes these effects into consideration and provides a very compact and cost effective combination of all the advantages these components can offer.

Picture 3: FN 3400 combines the advantages of line reactor and EMI filter

4.2 Line reactor versus isolation transformer

In the early days of VSDs the installation often needed a voltage step-up or -down and this was provided by a transformer, which also isolated the drive from the supply. It was a costly part of the system. More modern drives have internal isolation and motors have a wider range of voltages, so the established need for the isolation transformer is largely gone, and with it the cost of systems has fallen.

But the leakage inductance of the isolation transformer also protected the drive from the supply and vice versa. With this missing, there is still the need for some measure of protection, which is offered by the line reactor. A line reactor is substantially cheaper and smaller than an isolation transformer of equivalent power rating; a quarter of the cost and a tenth of the size and weight is typical. It protects the interface to the supply but does not give galvanic isolation nor a voltage conversion.

5 Summary – costs and benefits

A system supplier will always seek the lowest cost solution for a given specification. On the face of it, a line reactor is an added cost which does not apparently contribute to the basic function of the system. But this cost must be set against a range of benefits that occur in operation:

- reliability is improved, since power supply transients are less likely to damage the semiconductors and reduced peak currents will lengthen the lifetime of the capacitors
- downtime is reduced, since utility overvoltage surges are less likely to cause nuisance trips
- other users of the supply are pacified, since harmonic and commutation notch pollution is controlled
- the utility is pacified, since its connection constraints are achieved
- other system components such as the EMI filter can be cost-reduced
- line losses due to excessive harmonic heating are reduced, leading to lower operating costs.

In addition, using an output filter or reactor also has the benefits of improving motor and drive reliability and lifetime, and reducing electrical and acoustic noise pollution. Schaffner's range of line reactors and filters can relieve a number of problems in modern power applications, and are a worthwhile addition to the system builder's armoury.

For additional information and technical datasheets, please contact any Schaffner sales point or representative. Please visit *www.schaffner.com* for contact details.