# Harmonic mitigation for AC variable frequency pump drives

**Pump applications increasingly use AC variable speed drives. However, their operation introduces harmonic distortion of voltage supplies, which can cause serious problems. Ian Evans reviews the detrimental effects of harmonic distortion, the recommendations that have been put in place by different countries to minimize the problems, and the passive and active harmonic mitigation solutions currently available.**

The increase in the application of AC variable frequency drives over the past 15 years has been phenomenal as costs and physical sizes have reduced significantly whilst reliability is certainly no longer an issue.

One of the original growth areas for AC drives worldwide was in pumping applications (Figure 1). This is not surprising, since induction motors for pumpsets represent around 50% of all three-phase motors purchased globally. The benefits of variable speed pumps are now widely recognized – energy efficiency, decreased pump maintenance, ease of automatic control being the salient ones.

## International harmonics recommendations

An issue, however, that is giving increasing cause for concern throughout the world is the harmonic distortion of voltage supplies caused by the non-sinusoidal currents drawn during the power conversion process inside drive converters and other types of electronic equipment. In order to limit the magnitude of harmonics in the electricity supplies, various countries now implement harmonic recommendations. In North America and, to a major degree, internationally, IEEE 519 (1992) is the recognized 'standard'. In the UK, the new Engineering Recommendation G5/4 (2001) came into force in 2001 for equipment connected to the public electricity supply network (i.e. not connected to discrete generators). Many other countries have their own harmonic recommendations and standards or use the above.

Harmonics were encompassed in the EU EMC Directive (50 Hz – 2 kHz) as from 1 January 2001, with products, mainly for domestic use, up to 16 A per phase requiring mandatory harmonic mitigation to comply with IEC/EN 61000-3-2. However, AC variable frequency drives can be classed as 'professional equipment' and are at present accepted without limits under this standard. IEC/EN 61000 3-4 (to be replaced by IEC 61000-3-12) is for similar equipment up to 75 A per phase. It is unclear whether these standards will become mandatory in the EU EMC Directive in the near future with regards to variable speed drives.

Figure 1. Municipal waterworks – a typical pump application.

### North America

The North American IEEE 519 (1992) is possibly the best example to date of harmonic recommendations. It is the most easily understood – the maximum harmonic current permissible at a designated point of common coupling (PCC) being related to the short circuit capacity of the supply. (It is worth noting that the system impedance is inversely proportional to the fault level: the higher the fault level, the lower the voltage distortion for a given level of harmonic current. The higher the $I_{SC}/I_L$ [short circuit current to load current ratio], the higher the level of harmonic current that can be absorbed without producing excessive voltage distortion.)

**TABLE 1: NORTH AMERICAN IEEE 519 (1992) RECOMMENDATIONS (120 V – 69 kV)**

| $I_{SC}/I_L$ | Maximum current distortion in % of $I_L$ for individual harmonic orders | | | | | TDD |
|---|---|---|---|---|---|---|
| | <11 | 11-17 | 17-23 | 23-35 | >35 | |
| <20 | 4% | 2% | 1.5% | 0.6% | 0.3% | **5%** |
| 20<50 | 7% | 3.5% | 2.5% | 1% | 0.5% | **8%** |
| 50<100 | 10% | 4.5% | 4% | 1.5% | 0.7% | **12%** |
| 100<1000 | 12% | 5.5% | 5% | 2% | 1% | **15%** |
| >1000 | 15% | 7% | 6% | 2.5% | 1.4% | **20%** |

Notes: $I_{SC}$ = Short circuit current at point of common coupling (PCC). The PCC can be considered as the connection point between linear and non-linear (harmonic-producing) loads.
$I_L$ = Maximum demand load current (fundamental) at PCC.
TDD = 'Total demand distortion' of current (expressed as measured total harmonic current distortion, per unit of load current. For example, a 30% total current distortion measured against a 50% load would result in a TDD of 15%).

An important point, according to IEEE 519 (1992), is that "within an industrial plant, the PCC is the point between the non-linear load(s) and other loads". This should ensure that if IEEE 519 (1992) if fully complied with there will be no possibility of damage to, or adverse effects upon, the equipment connected within that plant or premises, subject to the correct operation of any harmonic mitigation measures employed therein. The North American IEEE 519 (1992) defines the maximum recommended voltage distortion (or total harmonic distortion of voltage, $V_{THD}$) for 'general systems' to be 5%, with no more than 3% of any individual harmonic. For 'special applications' such as hospitals and airports a lower limit of 3% applies. For 'dedicated systems' with 100% converter load (that is, no non-linear loads) a higher limit of 10% voltage distortion is permitted.

In IEEE 519 (1992) the permitted current distortion varies with respect to the system fault level and the total load demand as illustrated in Table 1.

## UK recommendations

In February 2001 the UK Electricity Association introduced new harmonic recommendations entitled *Engineering Recommendation G5/4 (2001)*. Unlike the US IEEE 519 (1992), these recommendations were introduced solely to protect the 'public electricity network' from the effects of harmonics at the PCC with other consumers. G5/4 (2001) considers neither the levels of harmonic currents within the consumer's own internal electricity network nor the effects of the harmonic currents and the subsequent voltage distortion, which may damage or otherwise adversely effect equipment in the plant or premises, should the limits be above the G5/4 recommended maximum levels.

Unlike IEEE 519 (1992), which is relatively simple to understand, G5/4 (2001) is more complex and details three distinct stages of assessment, each more complex than the preceding stage. A comprehensive review of G5/4 (2001) is beyond the scope of this article*. However, an excellent guide by Gambica entitled *Managing Harmonics – A Guide to the EA Engineering Recommendations G/4* is available in PDF format from the Gambica website (www.gambica.org.uk).

A simplified outline of the three stages of G5/4 (2201) as regards AC variable frequency drives is detailed below for guidance only. For further clarification contact both the drive vendor(s) and electricity supplier for further information. However, in view of present 'uncertainties' it is my opinion that the issue of harmonics and any possible mitigation requirements should be raised with drive vendors, irrespective of the kW rating.

### G5/4: Stage 1

The following AC variable frequency drives may be connected to low voltage supplies without assessment by the electricity supplier being carried out (subject to the existing voltage distortion not approaching 5%):

- AC drives compliant with EN 61000-3-2 (<16 A/phase)
- Single phase drives up to a total of 5 kVA per installation
- 6 pulse AC drives up to a total of 12 kVA
- AC drives up to a total 30 kVA if compliant with IEC 61000-3-4 (16–75 A/phase)
- 12 pulse AC drives up to a total of 50 kVA.

### G5/4: Stage 2

If the levels of harmonics exceed those for Stage 1, or where the existing voltage distortion is already close to the planning level, or the PCC is at medium voltage (MV; 6.6–22 kV), then a different approach is required. However, the following AC variable frequency drive loads can be connected at MV without further assessment:

- 6 pulse AC drives up to a total of 130 kVA
- 12 pulse AC drives up to a total of 250 kVA.

If existing voltage distortion is below 75% of the planning level the loads can be connected. However, if above the 75% level, detailed calculations are required to ensure the maximum voltage harmonic levels are not breached.

### G5/4: Stage 3

This applies to the PCC at 33 kV where the conditions of Stage 2 have not been met. Detailed harmonic analysis of the local network is required, especially where resonance is a possibility, including in remote parts of the network. A full description of the requirements of this stage is beyond the scope of this article.

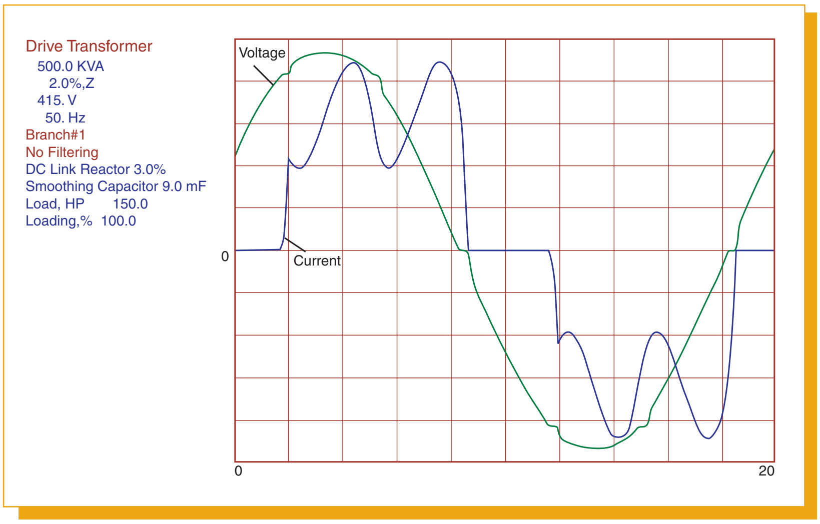


Figure 2. Typical AC PWM drive with 3% DC bus inductor; $I_{THD}$ = 39.5%.

## Why worry about harmonics?

Why is there such concern worldwide about harmonics? What actually causes harmonic distortion in the first place when AC variable frequency drives are used?

In simple terms, the design of AC variable frequency drives results in a pulsed current being drawn from the supply,

*Although G5/4 (2001) was introduced in February 2001, the associated Application Guide, *Engineering Technical Report ETR 122*, is still only available in draft form as yet incomplete. It is anticipated that it will be available end 2002/early 2003.

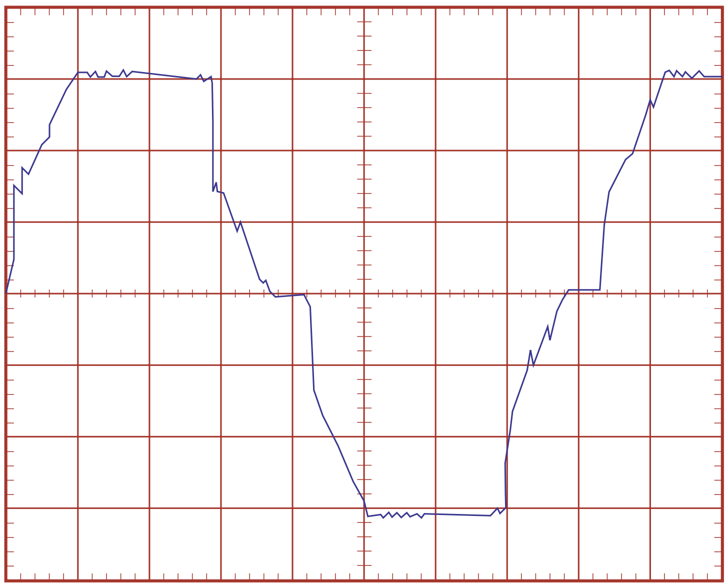

Figure 3. Effect of excessive harmonic distortion on a weak source (line voltage, no filter, THVD = 13.8%).

which contains harmonic currents (namely, additional currents that are multiples of the fundamental current frequency; for example, on installations with 50 Hz power, the 5th harmonic would be a 250 Hz current, the 7th a 350 Hz current, etc). In order to attenuate the magnitude of this pulsed current and associated harmonic currents, drive designers often install inductors in either the AC line or in the DC bus of the drive, and occasionally both. Figure 2 illustrates a typical AC 6 pulse PWM (pulse width modulation) drive fitted with a 3% DC bus inductor. In this example the total harmonic current distortion ($I_{THD}$) is 39.5%. (Without the DC bus inductor the $I_{THD}$ would be around 67%.)

Harmonic currents cause havoc in power systems, especially with generators, such as those found on remote pumping stations or on standby plant. These are 'weak' sources where impedances can be as high as 15–18% compared to 'stiff' sources (4–6%) more common in utility applications. The 'weaker' the source, the higher is the harmonic voltage distortion, for a given harmonic current distortion. Figure 3 illustrates the effects of excessive harmonic current distortion on the voltage supplied from a weak source, in this case a generator.

Typical effects of harmonic distortion include:

- Overheating and sustained damage to bearings, laminations and winding insulation on generators, causing early life failure. Similar effects on transformers: in the USA and Japan harmonics have resulted in fires in distribution transformers.

- Overheating and destruction of power factor correction capacitors. Danger of resonance (i.e. voltage amplification) if 'detuning reactors' are not fitted to the capacitor bank, causing catastrophic damage to capacitor bank and other equipment.

- Overheating of the stator and rotor of fixed-speed electric motors; risk of bearing collapse due to hot rotors. This is especially problematic on explosion-proof motors with increased risk of explosion; in any case if the voltage distortion is over the prescribed limit stated on the certification, the motor is no longer certified, losing any third party assurance as to its safety.

- Spurious tripping of electrical circuit breakers. Interference with electrical, electronic and control system equipment, including computers, radio communications, measuring devices, lighting, etc.

- Overheating of cables and additional risk of failure due to resonance. Decreased ability to carry rated current due to 'skin effect', which reduces a cable's effective cross-sectional area.

In the marine and offshore sectors, voltage distortion can be extremely severe. I have been advised by one classification body that they have evidence of up 24% voltage distortion on an offshore installation. Voltage distortion in the range 12–20% is relatively common – albeit not necessarily continuous – on these installations where up to 85% of the electrical load comprises mainly electric drives, including down-hole pumps. This is obviously why the marine classification societies are setting strict limits, usually 5%, on the permissible voltage distortion: to force harmonic mitigation to be installed.

## Harmonic mitigation methods

How do we further attenuate the harmonic currents produced by AC variable frequency drives to attempt to comply with harmonic recommendations? There are a number of mitigation methods available, some better than others.

### Traditional approaches

Traditionally, drive manufacturers have used phase shift transformers and modified drives to provide a greater level of harmonic attenuation, with 12 pulse being the most common. 18, 24, 36 and even 48 pulse designs are also used on occasion. 12 pulse mitigation provides levels of total harmonic current distortion ($I_{THD}$) from ~15% for polygonal autotransformers to 8–10% for the more expensive double wound types. Their use, however, lowers the overall efficiencies of the drive systems, often by 4–5 percentage points, primarily due to the losses of the transformers under harmonic loads. In addition, the phase-shifted limbs of the transformers must be carefully balanced and the pre-existing voltage distortion and voltage imbalance must be low otherwise the harmonic mitigation will be significantly degraded. This latter factor is not fully taken into account in G5/4 (2001).

### Active filters

More advanced solutions include active filters, which inject compensation current onto the system to 'cancel out' a major portion of the harmonic currents. Due to an active filter's low impedance (<1%), loads connected draw more harmonic current (~10–15%) than would be the case with no active filter in circuit. This additional harmonic current needs to be taken into account when dimensioning the active filter. The increased harmonic current may also be problematic to other 'upstream' connected loads. Faster responding active filters can give excellent mitigation performance (<5% $I_{THD}$) but some analogue-based active filters inject excessive reactive current into the power system if the harmonic load is light or is switched off, causing generator tripping and other problems. Active filters can be very expensive, often costing significantly more than the AC drives they are mitigating. However, as their popularity increases the prices will undoubtedly reduce. Reliability is still very much an issue, especially on remote applications. Active filters are very complex products and on-site commissioning engineers are necessary to achieve optimum performance.

## Sinusoidal rectifiers

Since the early 1990s most drive companies have experimented with 'active front ends' – also called 'sinusoidal rectifiers' – fitted to their AC variable frequency drives, with varying degrees of success. Replacing the conventional diode input bridge, these rectifiers normally produce a sinusoidal input current waveform with less than 5% $I_{THD}$, whilst also providing regenerative braking. However, the reliability of this approach is still very much an issue, especially when the drive is used for crucial duties; if the input bridge fails, the drive fails. In addition, due to the switching frequency of the input bridge, the drives also often require large reactor and passive filter networks to attenuate the electromagnetic and radiofrequency interference radiated signals and voltage ripple (at carrier frequencies), all of which could adversely effect other connected equipment. Prices are also still rather high, often being more than double the price of a conventional drive.

## A revolution in passive mitigation

During the past two years a new and unique form of passive mitigation, specifically designed for standard 6 pulse AC drives, has been gaining popularity in North America. The 'Lineator™', manufactured by Mirus International Inc (Mississauga, Ontario, Canada), consists of a series-connected multiple winding input line reactor and small capacitor bank, which can be applied to virtually any 6 pulse AC drive with either diode or SCR (silicon controlled rectifier) pre-charge input bridges to dramatically reduce the harmonic current. The revolutionary design achieves cancellation of all major harmonic currents resulting in an $I_{THD}$ of between 5–8% at full load operation. This dramatic reduction in harmonic currents is achieved through the patented multiple reactor winding design. This creates an output voltage waveform shape that allows the drive input diodes to conduct current over a longer time span and with a substantially lower peak value (Figure 4).

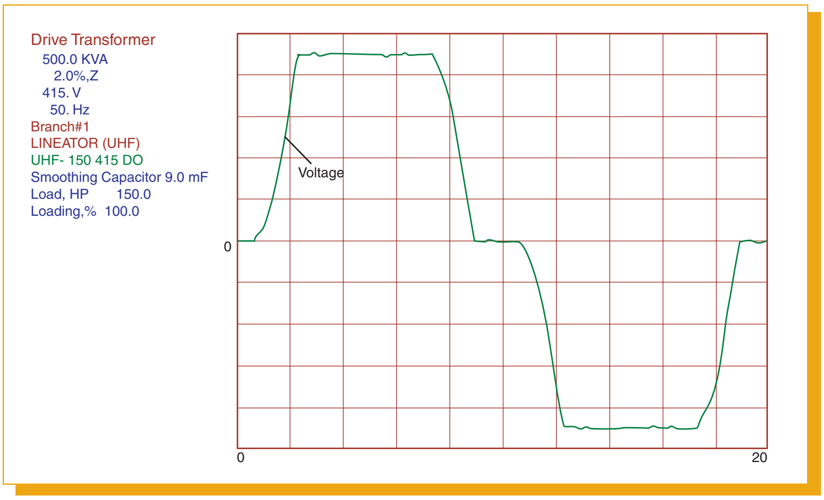


Figure 4. Effect of Lineator on AC drive input voltage waveform.

Figure 5 illustrates the effect of the Lineator on the same AC drive shown in Figure 2. In Figure 2 the drive used a 3% DC bus inductor, resulting in an $I_{THD}$ of 39.1%. With the Lineator connected the $I_{THD}$ dramatically dropped to 5.1%. For optimum performance AC line reactors or DC bus inductors should be omitted from the drive, ideally making the drive slightly less expensive.

The unique feature of the Lineator is the three-phase reactor design consisting of multiple windings formed on a common core. This design allows for a smaller capacitor bank without sacrificing harmonic mitigation performance or introducing unacceptable voltage drops. Due to the low capacitive reactance (<15% of rated kVA) the Lineator is compatible with all forms of power generators.

The Lineator can be applied to standard 6 pulse AC drives to achieve levels of harmonic mitigation normally associated with 18 pulse drives. Unlike active filters, the Lineator isolates the AC drive load from the effects of any pre-existing voltage distortion, very important in marine and offshore applications.

In addition, the Lineator's low losses (>99% efficiency) result in overall efficiencies of the Lineator/drive

Figure 5. AC drive as illustrated in Figure 2 fitted with Lineator. $I_{THD}$ = 5.1%.

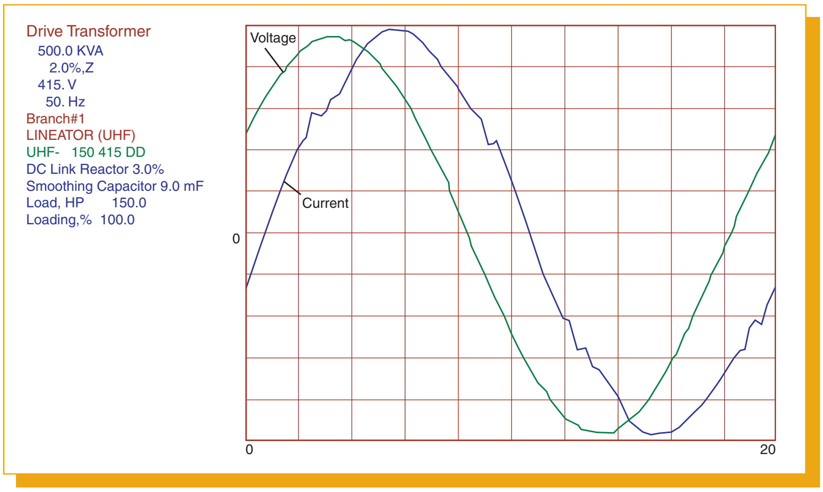

Figure 6. Three Lineators operating with 375 kW (500 hp) pump drives.

combination being typically 3–4% better than 12 or 18 pulse designs. This is crucially important in, for example, remote pumping stations supplied from generators where the cost of prime mover fuel is high or where the 'wire to water efficiencies' must be as high as possible to minimize running costs.

The Lineator can be applied to individual AC drives or to multiple AC drives and is easily retrofitted. It is currently available from 3 kW to over 2500 kW in voltages up to 750 V. Variants in development include: i) Lineator 2™, to provide drive-ready 12 pulse drives with 24 pulse performance; ii) a Trans-Lineator™ for MV/LV AC drive or LV/MV AC drive applications, the former often required for oilfield ESPs; and iii) an as-yet unnamed model for the mitigation of SCR-based AC and DC drives.

Lineator is supplied in chassis form for installation in drive cabinets or in stand-alone enclosures. Figure 6 illustrates a number of enclosed Lineator units operating with 375 kW (500 hp) pump drives.

Its rugged construction, simple design and inherent reliability, coupled with excellent harmonic mitigation performance and high efficiency, make the Lineator a serious contender for the majority of pump and other AC variable frequency drive harmonic attenuation requirements against IEEE 519 (1992), ER G5/4 (2001) or any other harmonic compliance criteria. ■

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