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## The Impact of Variable Speed Drives on Electrical Systems

P. 18

### INSIDE

**15** Controls & Sensors

**23** Plastics

**26** HVAC

**29** Coils

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# The Impact of Variable Speed Drives on Electrical Systems

*What You Need to Know About Harmonics—But Were Afraid to Ask*

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One undisputed requirement for a high performance system is the ability to closely match its output to the actual demand. Comfort, health, process variance, sound emissions, and energy performance benefit from enabling motors for variable speed operation. What are the potential side effects of this prescription? Power line harmonics, additional capacitance, or neutral conductor current?

## Definitions and standards

Draft standard IEC 52.800-x (1st edition) introduced the term power drive system PDS. It encompasses an electric motor with an associated electronic variable speed drive without restrictions to specific technologies. This standard will address the energy efficiency of these products. AHRI 1210-2011 Performance Rating of Variable Frequency Drives is limited to standard induction motors in combination with just VFDs, as its title implies precisely. One rating requirement of the latter standard aside from efficiency is “Power Line Harmonic Currents.” It standardizes the test method for harmonics caused by VFDs. Limits for

equipment emissions are specified in EN 61000-3-2 and in EN 61000-3-12, grouped by application and by nominal current consumption.

IEEE standard 519 Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems is concerned about the same phenomena but from the perspective of an overall plant, an entire facility, or the electric utility supplier. It does include recommended limits. (see Mike Olson article in the bibliography)

PDS such as VFDs and electronically commutated (EC) motors require unique power electronic units, either physically separate from the motor or within the motor casing. Such unit converts AC from the power line source to DC power that is temporarily stored in the so-called DC link circuit. The DC link voltage is then inverted to a frequency- and amplitude-modulated 3-phase AC output voltage that then finally excites the motor windings. The inverter output frequency and voltage amplitude determine the resulting motor shaft speed. **Figure 1** illustrates the flow of power in a PDS motor electronics unit.

Figure 1: Topology of a 3ph PDS

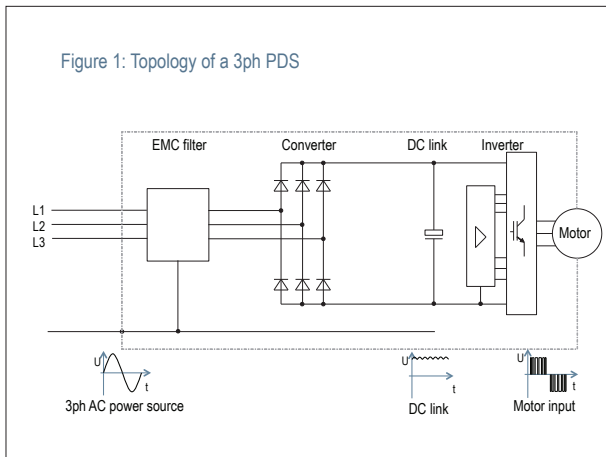


Figure 2: Power line current unmitigated

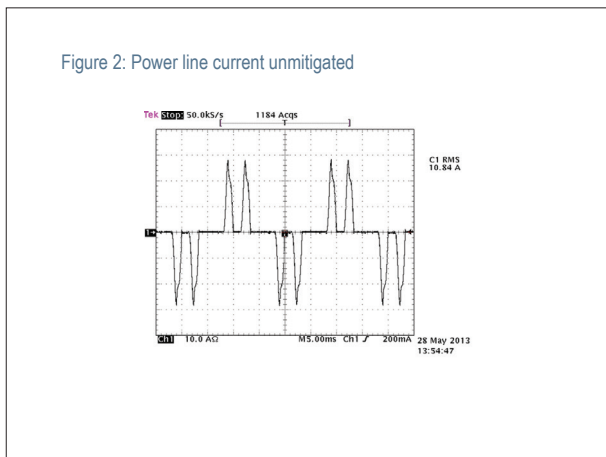


Figure 3: 3ph PDS with 2% line reactor

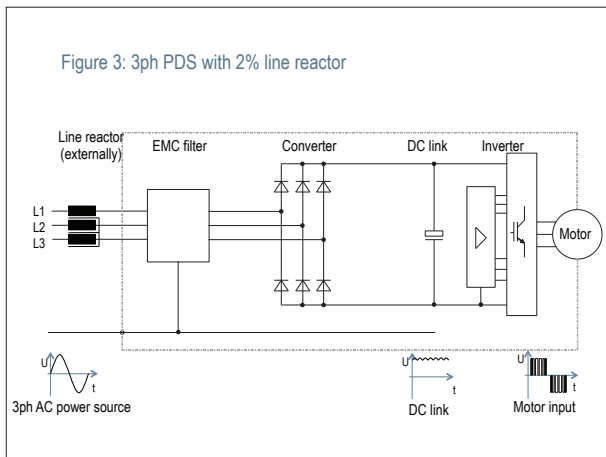
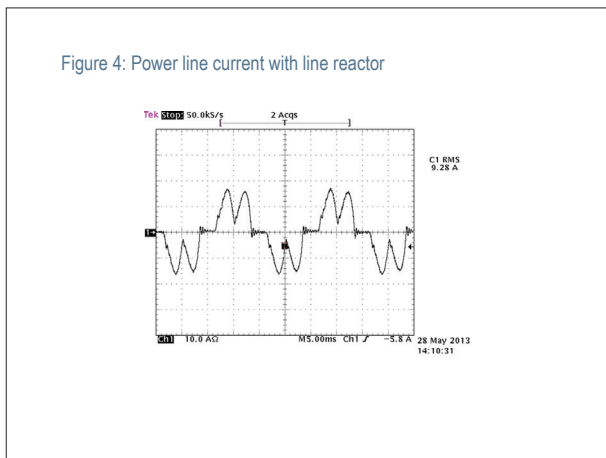


Figure 4: Power line current with line reactor



## Power line current harmonics

The converter with a passive rectifier bridge and its highly capacitive DC link circuit draws non-sinusoidal, non-linear power line input current. Distorted input current oscilloscope traces of a typical 6 kW PDS are shown in **figure 2**.

Three quantities describe power line interference commonly:

- ▶ Displacement power factor  $\cos \phi$  quantifies the phase shift between voltage and current in an AC circuit with purely sinusoidal waves. Otherwise it is not useful. It is a non-dimensional quantity. A sinusoidal voltage applied to a pure resistor causes a sinusoidal current without phase displacement and without drawing reactive power. The  $\cos \phi$  in this case is 1.0. If a capacitor or an inductor were added to this circuit then a reactive power component would occur and  $\cos \phi$  would be  $< 1.0$ .
  - ▶ True power factor  $\lambda$  is the quotient of effective power in watts over apparent power in volt-amps. Indirectly, it quantifies the reactive power of a load caused by both the phase displacement and by distortion from the sine wave of the fundamental frequency. Only if the current waves and the voltage waves are sinusoidal then the values of  $\lambda$  and  $\cos \phi$  are identical.
  - ▶ Total harmonic current distortion  $THD_i$  is the ratio of the geometric sum of all current harmonics up to the fortieth order over the fundamental current expressed in percent. Non-linear loads quite commonly produce  $THD_i > 100\%$ . Then the harmonics content of this current is greater than its fundamental wave.
- Displaced sinusoidal current waves and distorted currents are generally unfavorable for power supply systems. The associated reactive power adds to the load of

generators and of uninterruptible power supplies (UPS). Harmonics cause additional iron losses in power distribution transformers. Correspondingly, reactive power counts towards the sizing criteria of power sources including cables, switches, fuses and breakers. Electric utilities and suppliers of standalone power distribution systems therefore benefit from a power factor close to unity and from low total harmonic current distortion. Above mentioned standards help to assess these quantities and to establish various limits.

Line reactors and DC link filters provide methods for PDS to comply with these standards. These filters temporarily store some of the absorbed electrical energy and mitigate distorted current at the input of PDS.

## Line reactors

A line reactor rating of 2% means that the voltage drop across its filter choke at nominal current load amounts to 2%. Other common line reactors are 3% and 4%. However, their voltage drop on occasion reduces the maximum speed of a motor and the maximum possible output in cases of other load types. **Figures 3 and 4** relate to the aforementioned 6 kW EC motor example with an additional 2% line reactor.

## DC link filter choke

The filter of **figures 5 and 6** is integrated directly in the electronic power unit which avoids additional wiring in the field and minimizes the installation space requirements. The PDS layout accounts already for the filter voltage drop and the manufacturer guarantees the suitability of this filter based on the overall specification of the PDS.

Integrated DC link filter chokes or line reactors usually yield sufficient mitigation for PDS to meet the requirements of IEC 61000-3-12 that is based on common power supply systems. However,

# MOTORS

sensitive applications such as off-grid power systems may demand more severe power line current distortion limits: What often stems from attempts to save cost on generators or UPS is increased power source impedance which is then manifested in low relative short-circuit power  $R_{SCE}$ . If this situation leads to very low THDi specifications for electrical loads then comprehensive measures must be taken to mitigate harmonic current emissions.

## AC line input passive harmonics filter

These filters (figures 7 and 8) are voluminous and expensive but they mitigate harmonic current emissions well.

## Active converter

Active converters have become available recently. As integral parts of the electronic power units these can satisfy the most stringent specifications, reaching THDi of 2% or less. (Figures 9 and 10).

## Part load operation

Design-phase discussions of harmonics and of power factor mostly center on full load operation. Once a technician runs an actual bench test to evaluate equipment, a concern can arise: The power harmonics analyzer may display a  $\lambda$  and a THDi that appears worse than advertised: When that occurs, then the PDS likely operates at part load. It does consume reduced power just as predicted and the current draw of the fundamental frequency does drop accordingly. Yet the reductions of the higher order harmonic currents are less pronounced. (Figure 11) Remember that both  $\lambda$  and the THDi are ratios. The absolute values of both the numerators and the denominators grow smaller, but disproportionately. Therefore,  $\lambda$  and THDi values rarely matter

for part load operation.

## Standby operation

A so-called DC link capacitor mitigates DC voltage ripple at the converter output. If the motor draws no current from the DC link, the capacitor will remain charged. The DC link capacitor for this operating state cannot displace the current wave, does not consume idle power, and generates no power line harmonics. Simply, no charging current flows in a charged capacitor.

Standards for electromagnetic compatibility EMC limits demand that a PDS be equipped with an EMC filter. Usually, filter capacitors are connected between the power source phases or between a phase and the neutral conductor. The necessary capacitance depends on the emissions spectrum and the level of mitigation. Typical overall values vary from 100 nF to 10  $\mu$ F. This results in capacitive idle currents. Power trickles not just during standby but for as long as the PDS remains connected to the AC power line. A filter sized for a 5 A nominal phase current draws effective power of just about 4 W while the reactive power consumption is approximately 100 VAR. This capacitive amount provides a slight compensation when a PDS operates in parallel to inductive loads such as standard motors.

The DC link capacitor indeed buffers this power. But compared to the idle current of the EMC is its very low charge current of no consequence. (Figures 12, 13, 14) Harmonics mitigation does not provide a reason for separating a PDS from line power when the motor speed is set to zero. Additional control and switch gear would be necessary. Frequent power on and power off cycling reduces the life expectancy of PDS so that this method is acceptable rarely.

Figure 5: 3ph PDS with DC link filter choke

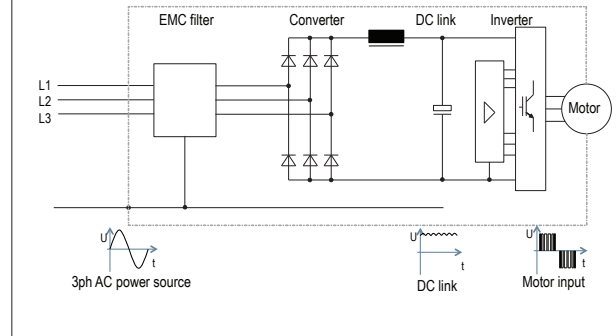


Figure 6: Power line current with DC link filter choke

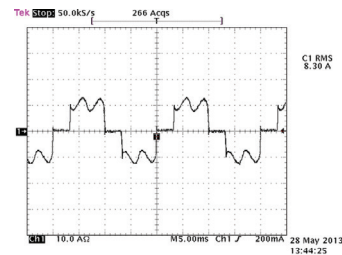


Figure 7: 3ph PDS with passive harmonics filter

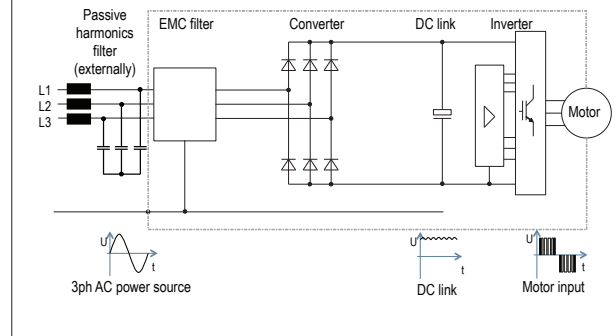


Figure 8: Power line current with passive harmonics filter

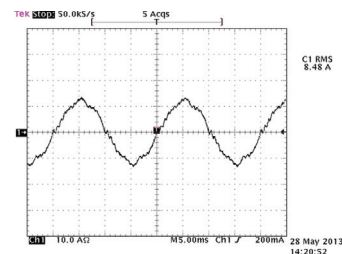




Figure 9: 3ph PDS with active converter

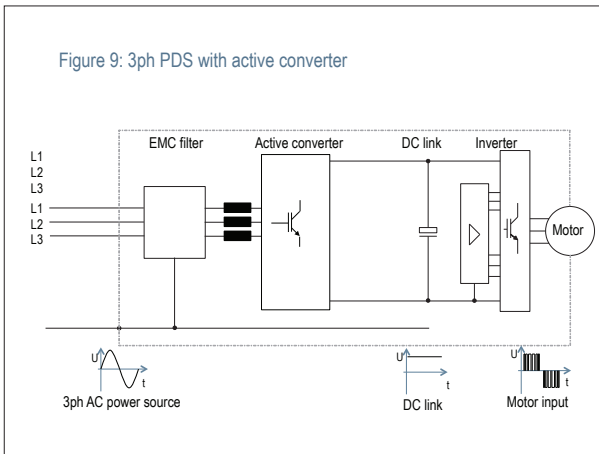


Figure 10: Power line current with active converter

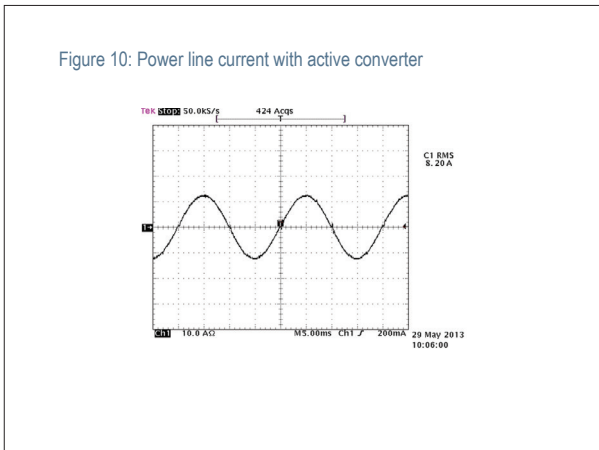


Figure 11: Harmonics of three-phase PDS for part load operation

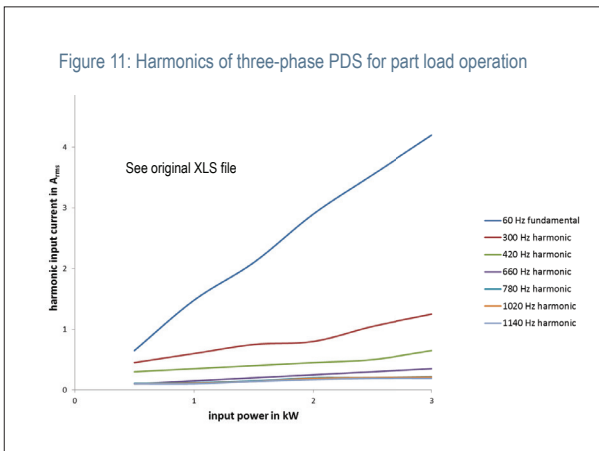
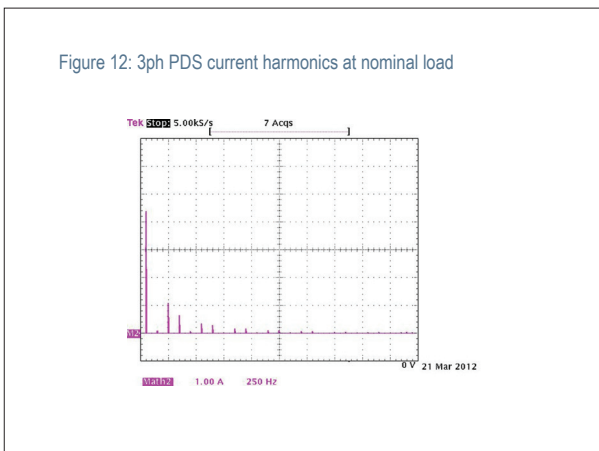


Figure 12: 3ph PDS current harmonics at nominal load



## Single-phase powered PDS

Triplen harmonic currents typically are negligibly low when a converter is powered from a three-phase (3ph) supply. However no such natural, internal cancellation exists with single-phase (1ph) supplied PDS. Here the third harmonic if left unmitigated easily approaches the amplitude of the fundamental current.  $\lambda$  is maybe 0.5 which then indicates that this unit draws reactive power  $\sqrt{3}$  times the value of its effective power. Happily, a 1ph powered PDS is generally just a small fraction of the load for a branch circuit, much less for an overall power distribution system. All reputable manufacturers have met applicable product standards for standalone PDS. Surprises only loom when an installation has many small PDS operating in parallel. Serious examples are packaged terminal air conditioners in hotels, hydronic circulation pumps, furnaces and air conditioners in townhouses, evaporator fans in supermarket display cases, and fan powered filter units in industrial cleanroom ceilings to name a few.

A 3ph distribution transformer can supply an array of single-phase loads. The transformer is utilized best if the overall load is similar for all three legs:

- ▶ A 3ph transformer with wye connected secondary windings and the center of the three phases wired to the output as a neutral provides a so-called four-wire 3ph supply. The three phases are  $120^\circ$  apart electrically. The 1ph loads are wired between this neutral and any of the three phases. The resulting phase-to-neutral voltage amplitudes are then  $1/\sqrt{3}$  times the transformer's phase-to-phase output voltage.

With purely linear loads the three sinusoidal phase current waves will cancel each other out

in the neutral conductor entirely. With non-linear loads, however, the three third harmonic phase currents are exactly in phase so that the 180 Hz current harmonic in the neutral conductor is the aggregate of the three individual third harmonics. (Figure 15). This mechanism generates an effective neutral conductor current value that amounts to a multiple of the phase current and the risk of overheating.

- ▶ If the transformer's secondaries are delta connected then there is no neutral and the 1ph loads are supplied from two phases of this three-wire 3ph system. The third harmonic appears trapped in the delta loop but this current still contributes to dangerously unsuspected phase conductor load.

The solution for this phenomenon is an active power factor controller PFC for single-phase powered PDS. It provides electrical performance close to ideal sinusoidal conditions and consists of an added circuit between the converter and the DC link. (Figure 16). An active PFC does take up additional space in the PDS, reduces maximum output power slightly, and increases the PDS' first cost. Its savings outweigh more costly and complex mitigation in the above described cases on the side of the power source.

## Summary

An electrical systems design process should always include a judgment about  $THD_i$ . Non-linear current draw causes non-linear voltage drop across the power source impedance. The engineer either specifies a suitable power supply and low impedance distribution system or encounters added cost for mitigation on all non-linear loads. A harmonic current emission limit stricter than EN 61000-3-2 and EN 61000-3-12 prevents the use of proven, standard PDS, may

# MOTORS

increase their size and weight, may reduce their maximum output, and therefore jeopardizes the cost savings potential from variable speed systems. ■

## References, Bibliography, Notes

European Committee for Electrotechnical Standardization CENELEC draft standard CLC 52800-x: Energy efficiency and Eco-design requirements for Power drive systems, motor starters, Power electronics and their driven applications [http://www.eco-motors-drives.eu/Eco/Documents\\_files/EuP-Lot-30-Task-1-5-Jun-2012-Draft.pdf](http://www.eco-motors-drives.eu/Eco/Documents_files/EuP-Lot-30-Task-1-5-Jun-2012-Draft.pdf)

International Electrotechnical Commission draft standard IEC 52.800-x (1st edition) Efficiency of frequency converters, power drive systems and complete drive systems

Canadian Standards Association CSA standard C393-12 Test methods for measuring power consumption in low and idle power modes of commercial and industrial equipment.

International Electrotechnical Commission standard IEC 61000-

3-2 Limits for harmonic current emissions (equipment input current  $\leq 16$  A per phase)

International Electrotechnical Commission standard IEC 61000-3-12 Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current  $> 16$  A and  $\leq 75$  A per phase

Air Conditioning and Refrigeration Institute standard AHRI 1210-2011 Performance Rating of Variable Frequency Drives

Olson, M.R. 2009 "Harmonic Distortion: Reality vs. Perception" Nov. 2009 HPAC Engineering Magazine <http://hpac.com/motors-drives/harmonic-distortion-reality-perception-1109>

2012 Ashrae Handbook HVAC Systems And Equipment chapter 45. Motors, Motor Controls, and Variable-Speed Drives

2011 Ashrae Handbook HVAC Applications chapter 56. Electrical Considerations

Figure 13: Oscillogram of 3ph PDS standby operation

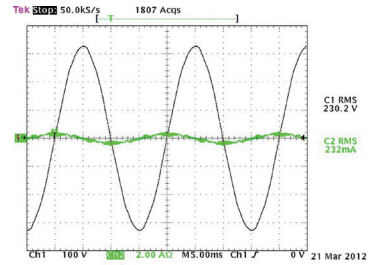


Figure 14: 3ph PDS current harmonics for standby operation

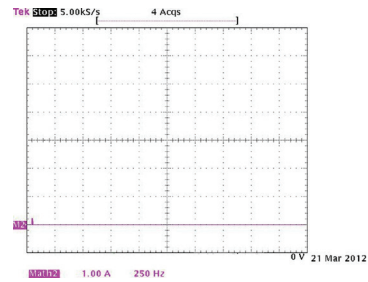


Figure 15: Third harmonic neutral problem with 1ph PDS

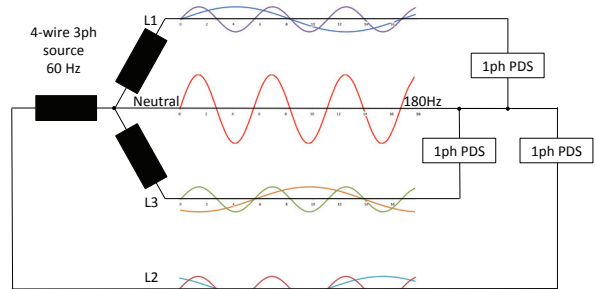
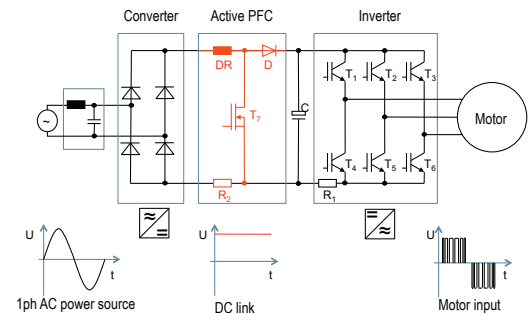


Figure 16: 1ph PDS with active PFC



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