Passive Harmonic Mitigation Solutions for Variable Speed Drives: Benchmarking LRC Filters Versus 18-pulse Rectifiers

Retain for future use.

Introduction

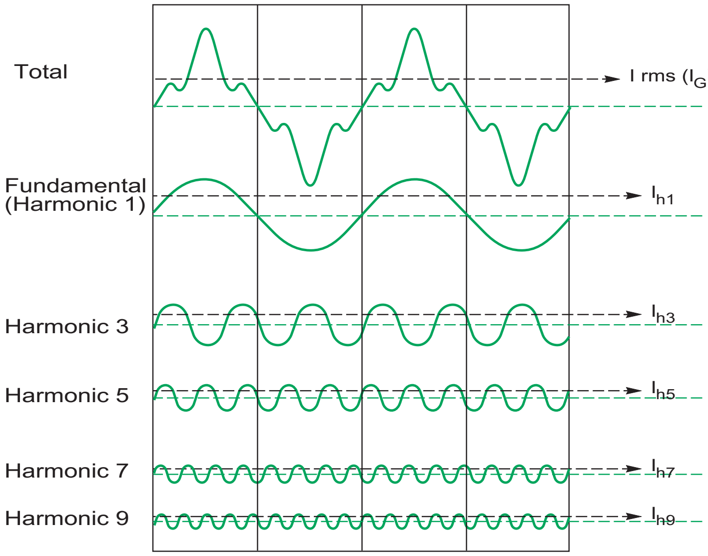
This paper is an introduction to line harmonics in variable speed drive applications. It presents benchmarking data with results analysis for LRC filter and 18-pulse rectifier solutions.

Every electrical circuit is a potential source of electrical interference, particularly when switching reactive loads. Most electrical interference is low level and has no noticeable effect on other branches of electrical equipment. Variable speed drives, however, are highly non-linear loads; input rectifiers produce a high level of harmonics that may affect the performance of other devices connected to the same electrical supply. Active or passive filters can be used to improve the power quality in the branch.

What Are Harmonics?

A harmonic current is a current that is a multiple of the fundamental frequency. For example, in a 60 Hz environment, the fifth harmonic is 300 Hz. Harmonic distortion can cause the power grid or its branch to carry extra power with frequencies that are multiples of 50 or 60 Hz. Harmonics can cause distortion of the normal sine waveform, and can cause equipment overheating and failure. Higher rank harmonics are a result of using non-linear loads that produce non-sinusoidal current. Three-phase systems present an advantage over single-phase systems because harmonics of rank 3 and its multiples (6, 9,12,15, and so forth) typically are self-canceling.

Figure 1: Harmonics Display



The Influence of Harmonic Currents

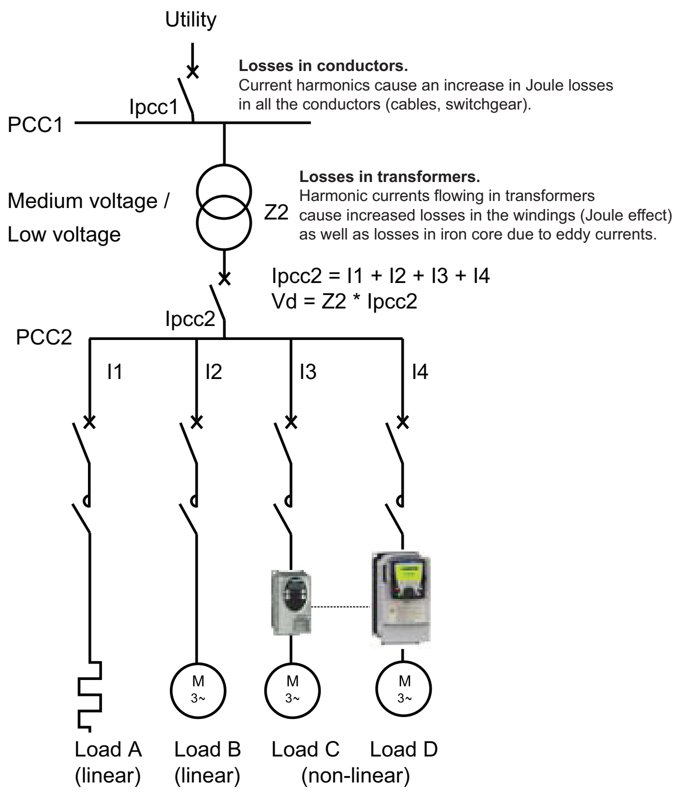
A typical power distribution system consists of several transformers, power lines, and switch gear. Each component of the system presents an impedance that may cause a voltage drop, depending on the current flowing through the system. Because most elements of the system are inductive, the voltage drop is proportional to the amount of current as well as its frequency:

$$V_d = I_{rms} \cdot Z$$
$$Z := \sqrt{R^2 + (2\pi\ f \cdot L)^2}$$

R = component resistance
L = component inductance
f = frequency

High harmonic content in the current causes voltage distortion that is conveyed to all devices connected to the system. Harmonic content in voltage and current may cause power losses, as well as unintended equipment behavior. Power losses directly affect both capital and operational expenditures related to the system/branch. Components must be properly sized not only to satisfy end load demands, but also to deliver additional power that is lost due to harmonics.

Figure 2: Power Distribution System



As shown in Figure 2, the voltage that supplies loads A and B may be distorted due to harmonics generated by the drives supplying loads C and D. The current Ipcc2 is a sum of currents from all 4 loads, and it contains harmonics. The voltage at Point of Common Coupling 2 (PCC2) normally would be sinusoidal; however, it is modified by the voltage drop (Vd) that is a result of current Ipcc2 flowing through the impedance of the transformer (Z2), cabling, and switch gear.

High-current harmonic content reduces power quality and consequently causes a number of problems:

- overloads on distribution systems due to the increase in the root mean square (RMS) current. If a distribution system is not designed for its scalability, harmonic content may disqualify it for use with non-linear loads.
- overloads on neutral conductors due to the summing of third-order harmonics created by single-phase loads,
- vibrations and premature aging of generators, transformers, and motors,
- premature aging of capacitors in power factor correction equipment,
- sufficient distortion of supply voltage to disturb sensitive loads, and,
- disturbances in adjacent communications networks (telephone and data).

Total harmonic distortion, or THD, is an important factor in an electric system's power factor (PF).

Power Factor and THD

The power factor of an AC power system is defined as the ratio of the real power flowing to the load, to the apparent power in the circuit. The real power is the capacity to do work. The apparent power is the product of the current and the voltage of the circuit.

It is possible to have a motor running on a line with a power factor of 0.7, but with a system efficiency is 0.94. On the other hand, it is also possible to have a system with an active filter (such as an AccuSine™) so the power factor is 0.99, but because of electrical losses and mechanical friction, the system efficiency is only 0.5.

In such systems, active power (P) represents the real power going into the drive where the current is in phase with the voltage; and, the apparent power (S) represents the total power, including harmonics and products of currents off the phase.

Because the drive introduces harmonics in current, some of the power is lost from a transformer due to its impedance. The transformer must be properly sized to satisfy the demand for both active power and power losses. The ratio of that extra power demand is proportional to Total Harmonic Distortion (THD) in current on the secondary winding of the transformer.

$$\mathrm{THD}_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1}$$

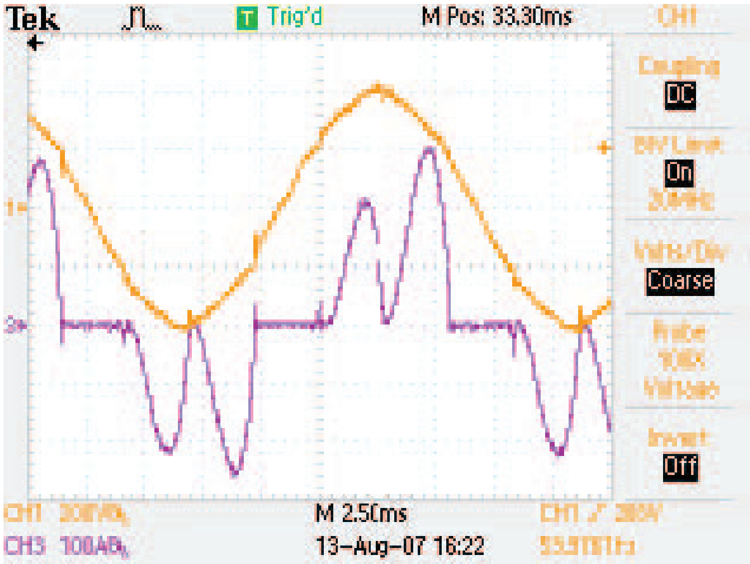
I_1- fundamental, I_h- harmonics

The power factor is proportional to THD in current:

$$\mathrm{PF} \sim \frac{\cos \varphi_{\mathrm{load}}}{\sqrt{1 + \mathrm{THD}_I^2}}$$

A typical 6-pulse drive input current waveform (see Figure 3) contains four pulses per sine period, representing a DC bus capacitor charging cycle. Such current is the main source of harmonic distortion in rectifier circuits and may cause THD to reach up to 150% in RMS value.

Figure 3: 6-pulse Drive Input Voltage and Current Waveforms



Harmonics Mitigation

A variety of methods can be used to mitigate harmonic distortion. All involve additional cost in the power system, and there is some disagreement over which solutions are the most cost-effective. The most obvious impacts of harmonic distortion are increased power draw and deterioration of power quality, which have both a technical and financial impact on any enterprise. Proper harmonic mitigation may improve competitiveness of a company's product by reducing cost in the target installation.

Some of the most popular, equipment-level harmonics mitigation solutions include:

- Passive filters (broadband)

  An LC or RC circuit tuned to each of the harmonics to be filtered, installed in parallel with the device that generates harmonic distortion. The filter shorts harmonic currents, preventing the flow of harmonics to the power source. This solution can be implemented after commissioning.

- Active filters (power conditioners)

  Active filters are systems employing power electronics, installed in series or in parallel with the non-linear load. These systems cancel harmonic currents/voltages and prevent distortion on the power system. In most cases, this solution is used at the installation level, filtering harmonics coming from multiple branches of non-linear loads.

- Multi-pulse input rectification

  A 12-or 18-output transformer feeding multiple rectifiers that supply the same DC bus in the drive. Each of the transformer's output voltages is phase shifted to minimize the ripple in DC bus voltage. As a result, the bus voltage requires minimal filtration and provides high constant power to the inverter. Although this solution provides high system efficiency, it is costly, heavy, and bulky.

- Active front end

  This solution is based on active, controlled input rectifiers that are driven from a processor system. The system monitors the power quality on the drive input and the drive's input rectifier to minimize the amount of harmonics in the input current. This solution is costly and is recommended for systems requiring the highest power quality.

- Slim DC link (C-less)

  This solution is based on low DC bus filter capacitance. In regular 6-pulse drive systems, most of the harmonics in current are generated while filter capacitors are being charged. The level of harmonic currents depends on filter capacitance; therefore, filters with low capacitance generate low levels of harmonics. This solution has some trade-off since with lower DC bus capacitance, the drive controller has a lower capacity to ride through supply voltage sags. This solution is intended for applications with high-inertia mechanical loads.

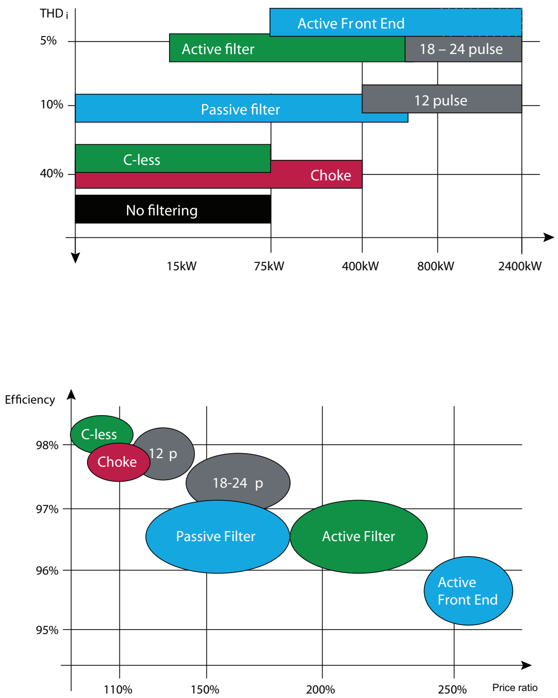
- Line and/or DC bus chokes

  Inductors installed in series with the drive input and/or the DC bus provide impedance that grows with the frequency of harmonics in the current passing through. This solution is recommended for use with typical 6-pulse drives and can be externally implemented without changes to drive circuitry. The disadvantage of using a drive input choke is that it best filters high rank harmonics while low rank harmonics are typically of highest current magnitude and are the most concerned.

Harmonics mitigation systems can be compared in two ways:

- applicability to specific power demand, or
- solution cost.

Figure 4: **Harmonics Mitigation Systems Comparison** [1]



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[1] Results shown are typical. Actual results may vary based upon environment, power quality and equipment used.

Testing an 18-pulse Rectifier Against a Passive Filter

To compare the harmonic mitigation effectiveness of an 18-pulse rectifier with that of a passive filter, the same variable speed drive was tested in the following environments:

- Constant speed / variable torque at 100%, 75%, 50%, and 25% of nominal load
- Constant speed / variable torque at 100% and 75% of nominal load with input voltage unbalance of 1% through 5%

Test Setup

A 75 hp, 2-pole motor served as the test motor for both drives. It was mounted and coupled to an Eddy Current Dynamometer (EC Dyno) that provided a controlled load.

The motor was loaded to 100%, 75%, 50%, and 25% for both drives. All electrical input and mechanical output parameters were recorded at each load point, as well as harmonic distortion data (THD). Corresponding data was taken at multiple line voltage unbalance conditions – minimal, 2%, 3%, 4%, and 5%, for the full load and 75% load points. The 50% and 25% load points are operated at minimal line unbalance.

Figure 5 shows the layout for the test setup. Figure 6, Figure 7, and Figure 8 illustrate the 18-pulse transformer, test motor, and MTE Matrix filter used in the test.

Figure 5: Test Setup for Variable Speed Drives

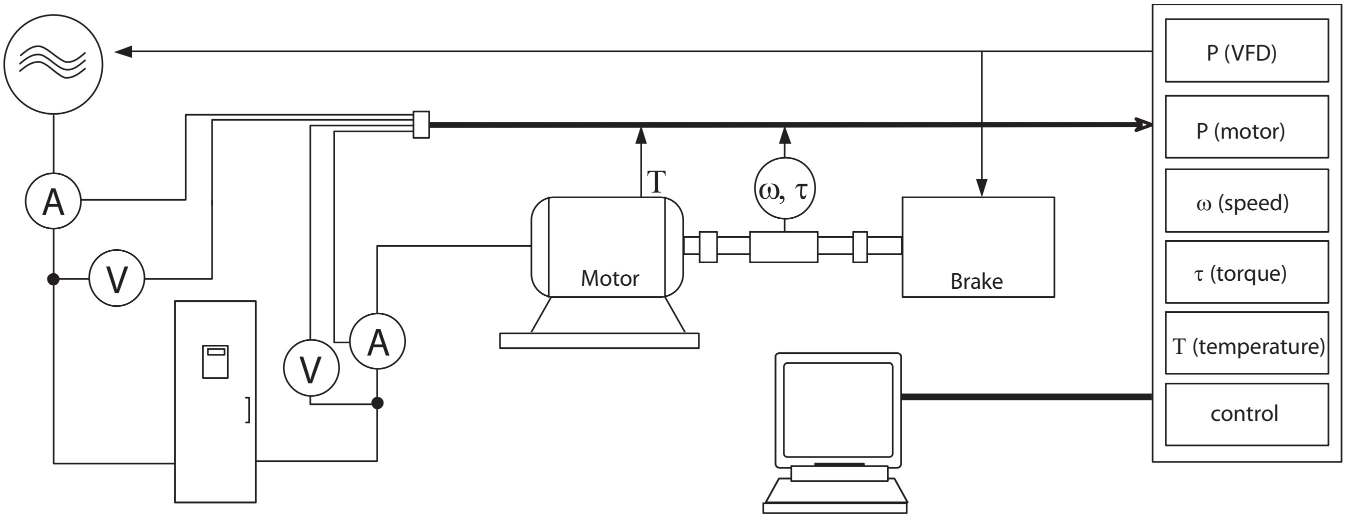


Figure 6: 18-pulse Transformer

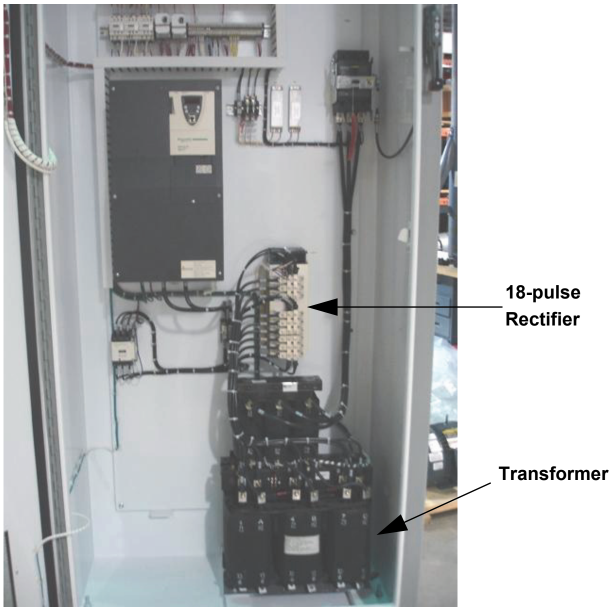
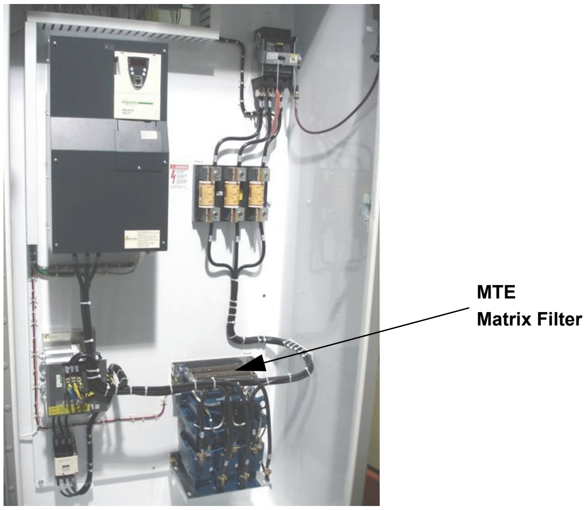


Figure 7: Test Motor

Figure 8: MTE Matrix Filter



Test Results

Figures 9 through 19 show the test results:

Figure 9: MTE Matrix Filter: System Efficiency and THD Levels

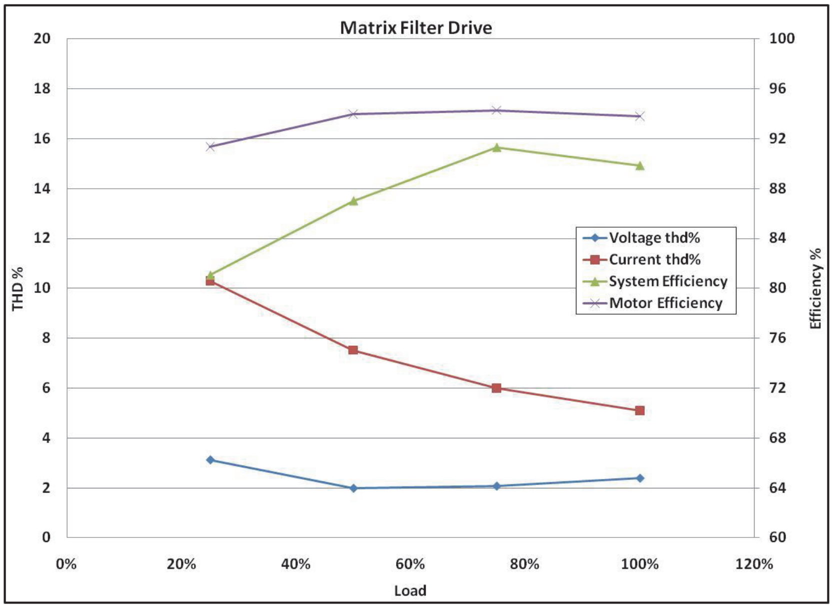


Figure 10: MTE Matrix Filter: Power Factor and THD Levels

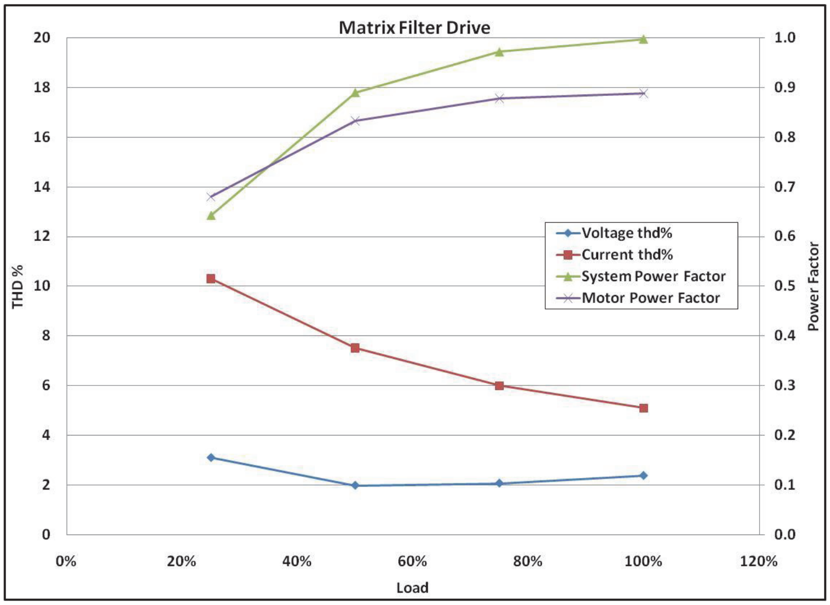


Figure 11: 18-Pulse Rectifier: System Efficiency and THD Levels

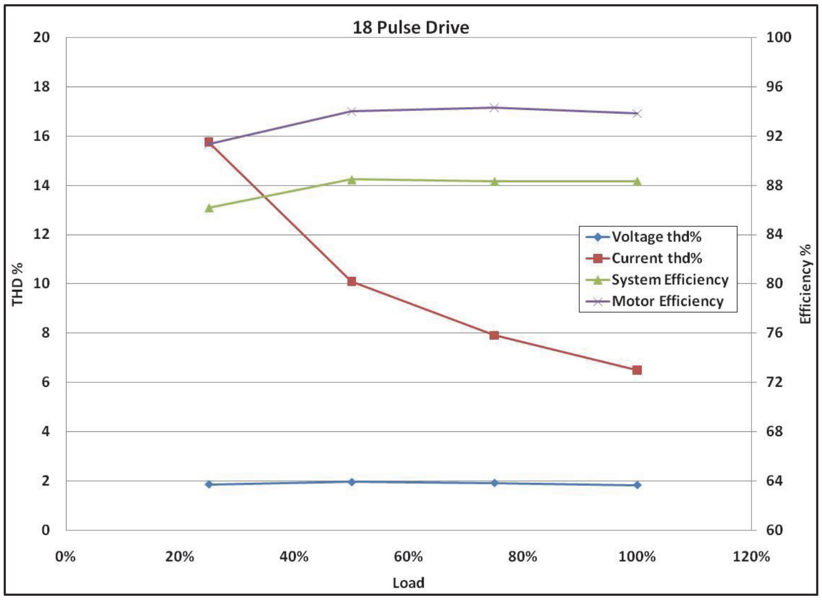


Figure 12: 18-Pulse Rectifier: Power Factor and THD Levels

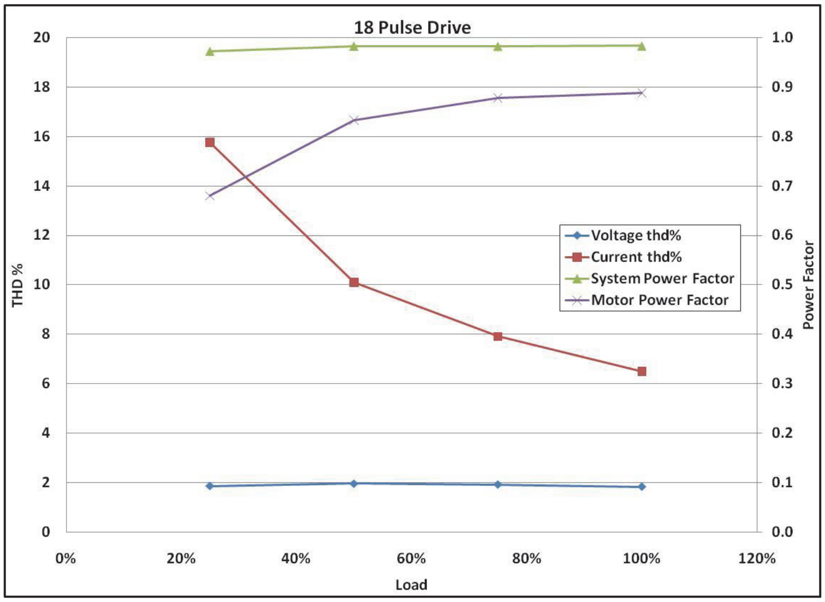


Figure 13: Power Factor as a F**unction of Line Unbalance**

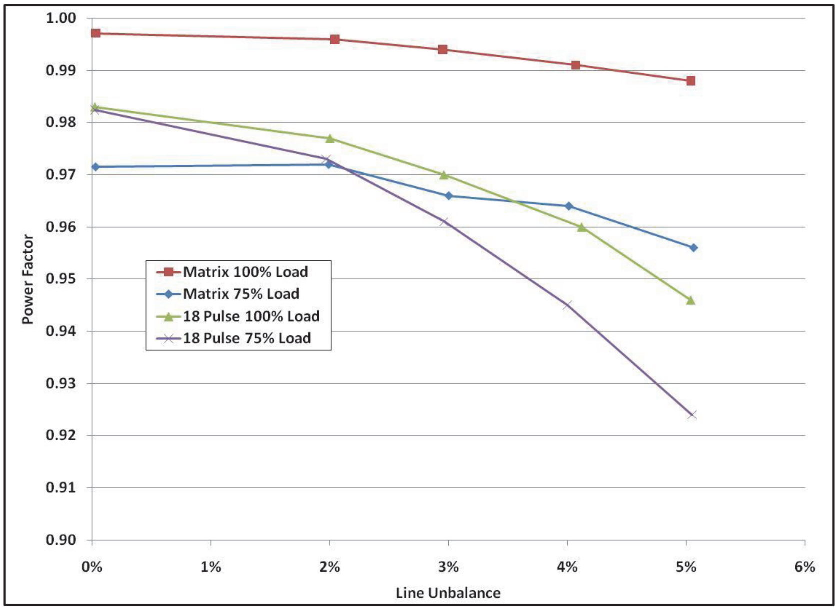


Figure 14: MTE Matrix Filter: Input Voltage and Current Waveforms

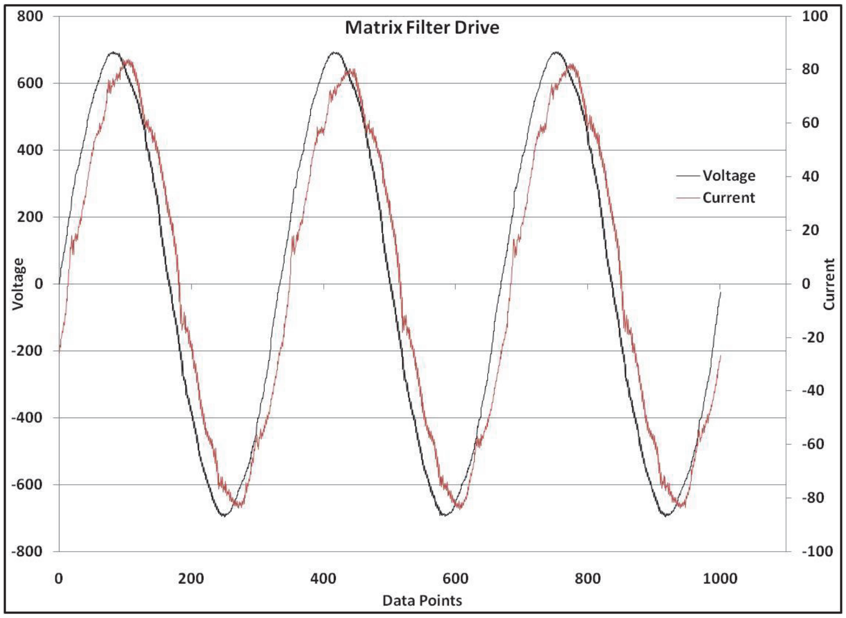


Figure 15: 18-Pulse Rectifier: Input Voltage and Current Waveforms

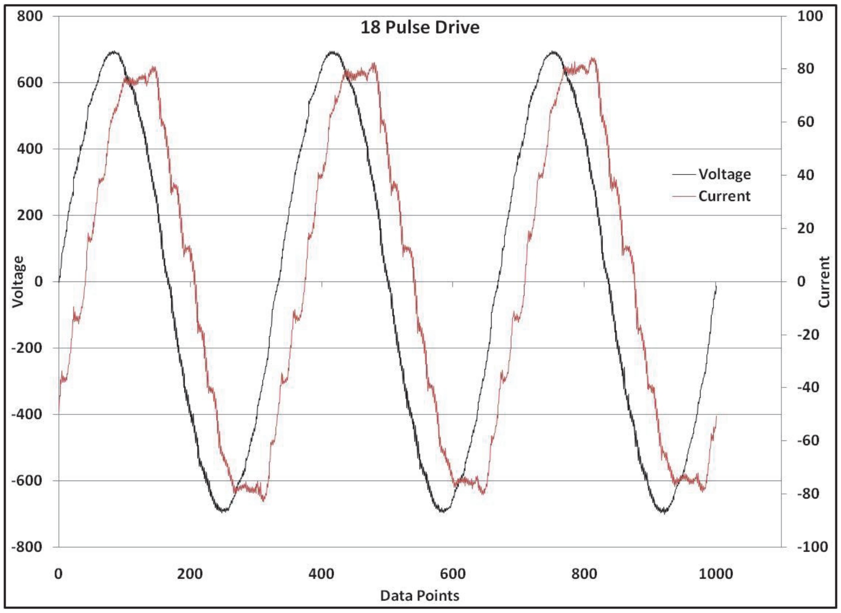


Figure 16: MTE Matrix Filter: Harmonics Distribution (per phase)

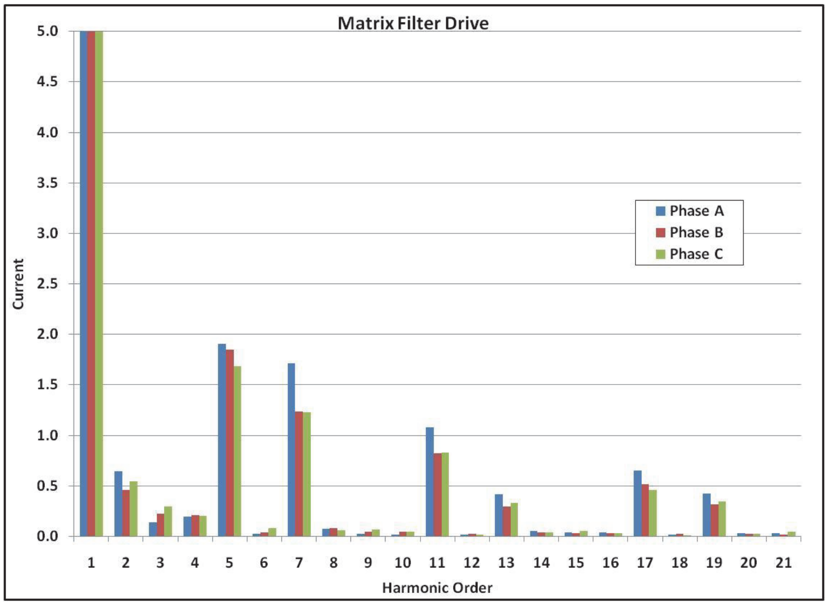


Figure 17: 18-Pulse Rectifier: Harmonics Distribution (per phase)

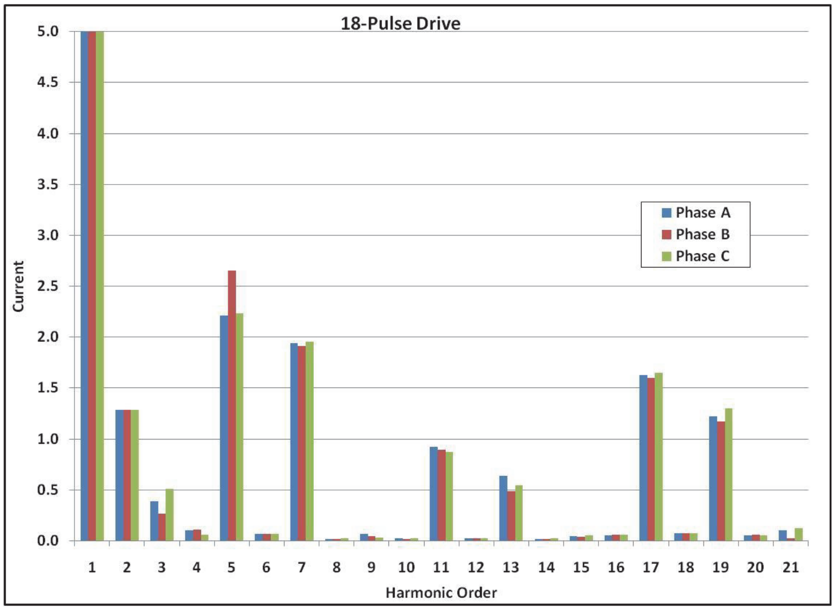


Figure 18: 18-Pulse Rectifier: THDi Levels as a Function of Line Unbalance at 100%of Nominal Load

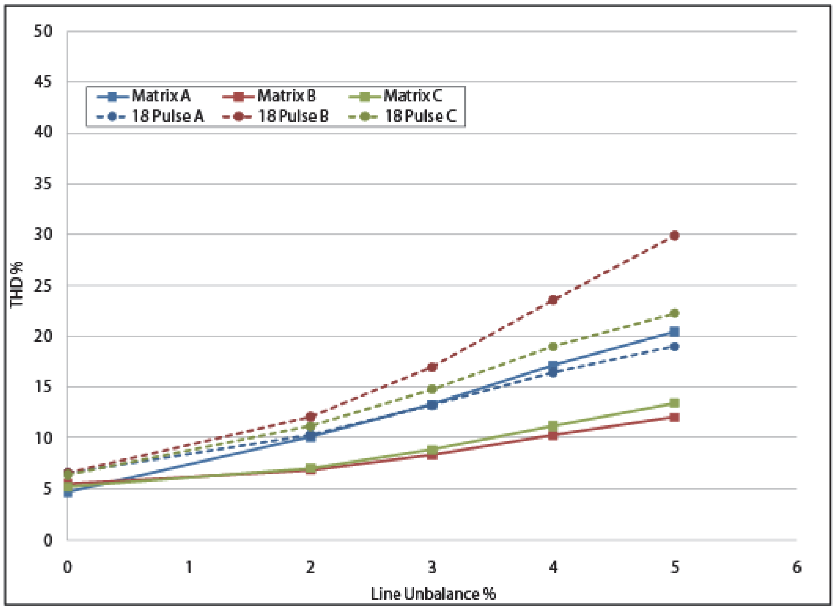
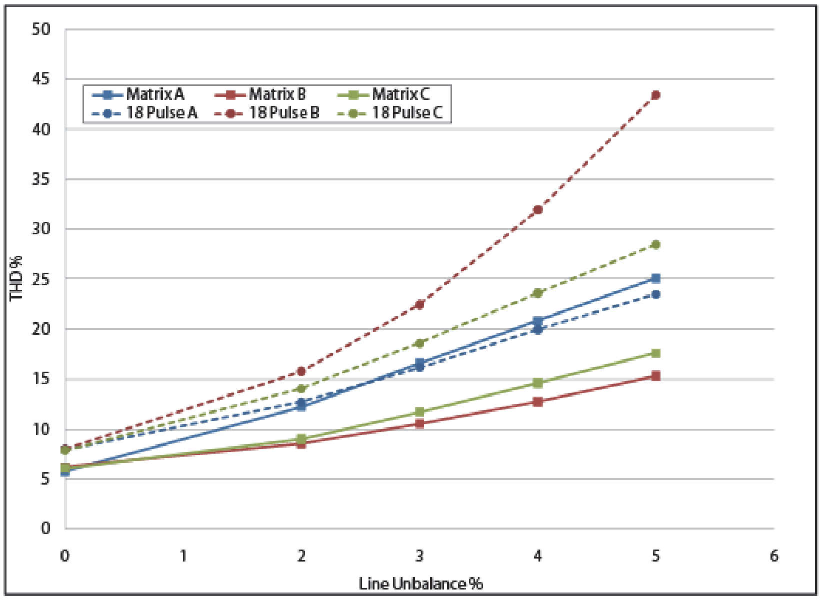


Figure 19: 18-Pulse Rectifier: THDi Levels as a Function of Line Unbalance at 75% of Nominal Load



Conclusions

Both tested harmonic mitigation systems reduced harmonics down to acceptable levels. With minimal line voltage unbalance, both solutions provided comparable performance:

Solution	MTE Matrix Filter	18-pulse Rectifier
THDu	2–3%	2%
THDi	5–10%	6.5–16%
System PF	0.65–0.99	0.98
System Efficiency	80–90%	86–88%

The level of current harmonics is slightly higher for the 18-pulse rectifier solution; however, the voltage THD stays very low, which indicates a very low short-circuit impedance of the source transformer.

In an environment with voltage unbalance in one of the source phases, the MTE matrix filter performed significantly better. The main reason for this is that the 18-pulse rectifier does not provide any harmonics filtration; it is designed to prevent harmonics from being created by reducing the level of ripple. Therefore, it does not mitigate harmonics that result from phase unbalance. The matrix filter provides filtration regardless of the source of harmonics and will perform better in mixed environments.

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