

# Adjustable Frequency Drives Input Harmonic Mitigation Matrix Filters

and

**IEEE – 519**

**120 V - 69,000 V**

Wayne Walcott

March 5, 2009



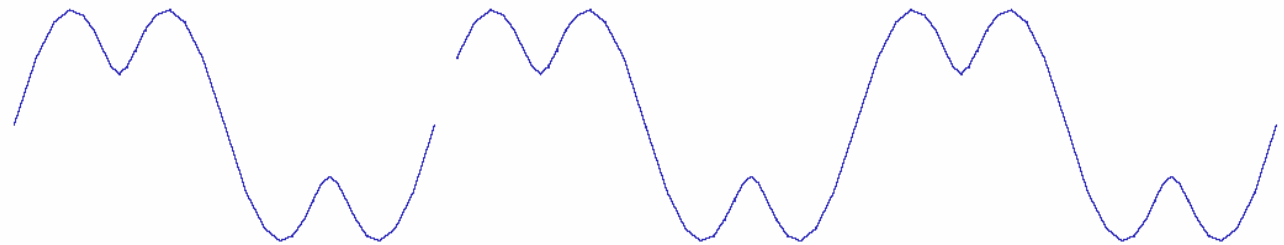
# Harmonic Current Formula

$$\text{THID} = \frac{\sqrt{\sum_{h=2}^{\infty} (I_h)^2}}{I_1} \times 100\%$$

Where:

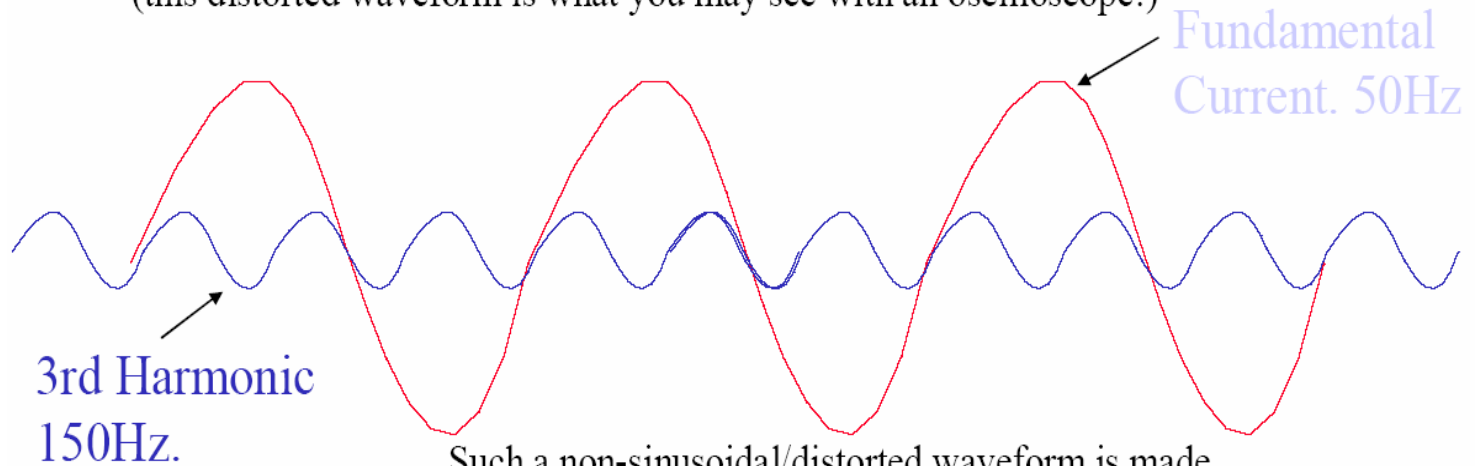
- $I_h$  = magnitude of individual harmonic content (RMS amps)
- $h$  = harmonic order
- $I_1$  = fundamental current (RMS amps)

# What are Harmonics



Voltage/current waveform

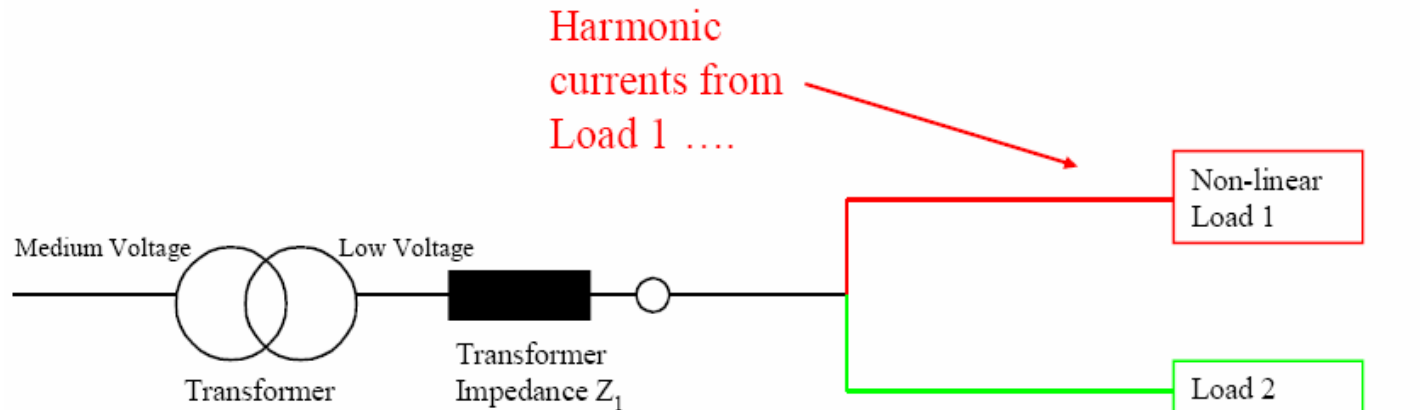
(this distorted waveform is what you may see with an oscilloscope!)



Such a non-sinusoidal/distorted waveform is made up from these two sinusoidal waveforms



# Harmonic voltage distortion from nonlinear Harmonic current loads



The harmonic currents are local to the load  
- they are directly associated with the non-linear load and no other part of the system  
- they are a measure of the product's performance

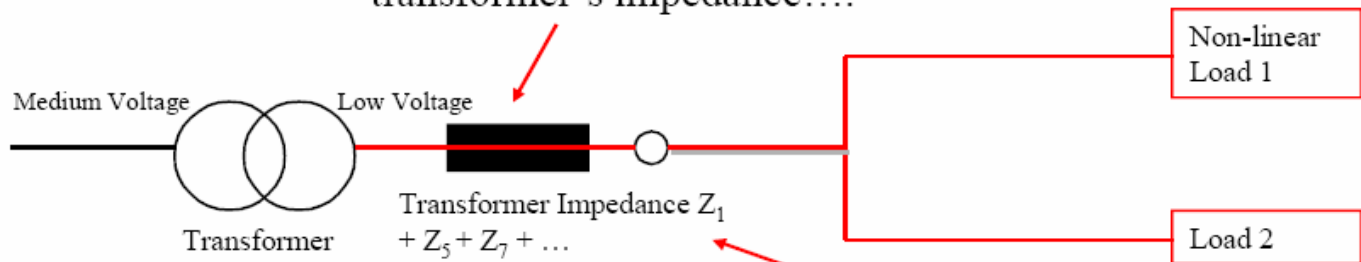
They do not result in any additional losses in the cables to Load 2, only in those to Load 1 (and in the transformer ...)

... are independent of Load 2



# Results of Harmonic currents

However the harmonic currents from Load 1 pass through the transformer's impedance....



- Impedance of a reactor =  $2 \times \pi \times f \times L$ 
  - i.e. is proportional to the frequency
- Impedance of Transformer at harmonic frequencies  $Z_n$  related to impedance at fundamental frequency  $Z_1$  by equation:
  - $Z_n = n \times Z_1$
- Voltage drop across impedance increases proportionally with frequency/harmonic number and with the level of harmonic current

... resulting in voltage drops across this impedance which can result in the distortion of the transformer's terminal voltage waveform .....

...Harmonic Voltage Distortion .....

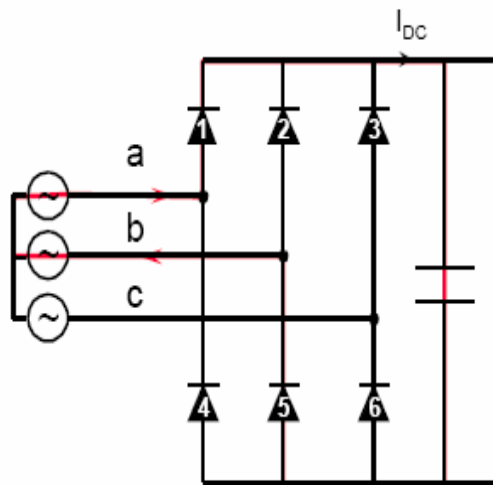
which could affect Load 2 and any other loads on the system.

# Where do harmonics come from

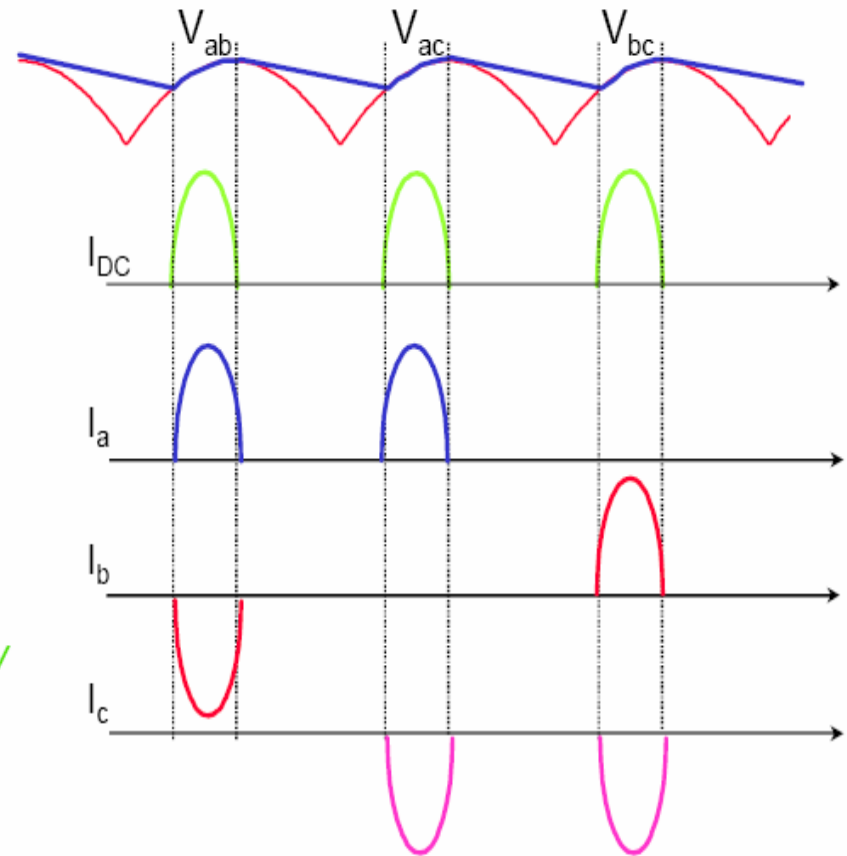
- Any non-linear load
- A non-linear load is any load which draws current which is not proportional to the voltage applied. Such as:
  - Controls for arc welders, furnaces, ovens.
  - AC or DC motor drives.
  - Any AC to DC rectifiers
  - Un-interruptible power supplies (e.g. in PCs, TV, VCDs, DVDs...)
  - Fluorescent lights.
- In the past 15 years there have been a dramatic increase in the use of such loads, particularly in the domestic supply network .... Hence an increasing concern about harmonics!



# 3 phase six pulse bridge bus supply



- *Non-sinusoidal currents are drawn from the supply*
- *Pulsating power from the supply source*



# Why does a 6 pulse bridge produce odd harmonics?

- Harmonics dependant on pulse number of rectifier.

- $H = (P \cdot N) \pm 1$

- (P= No of pulses; N = any integer)

Therefore on a 6 pulse system,  $H = ((6 \times 1) - 1) = 5$ .

5th(**250Hz**)/7th(**350Hz**)/11th/13th etc....

- Theoretically the magnitude decreases as the harmonic frequency increases ( $1/n$ ) e.g. 5th =  $1/5 = 20\%$ .



# Displacement power factor:

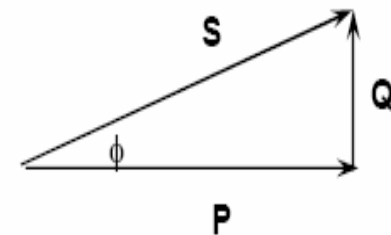
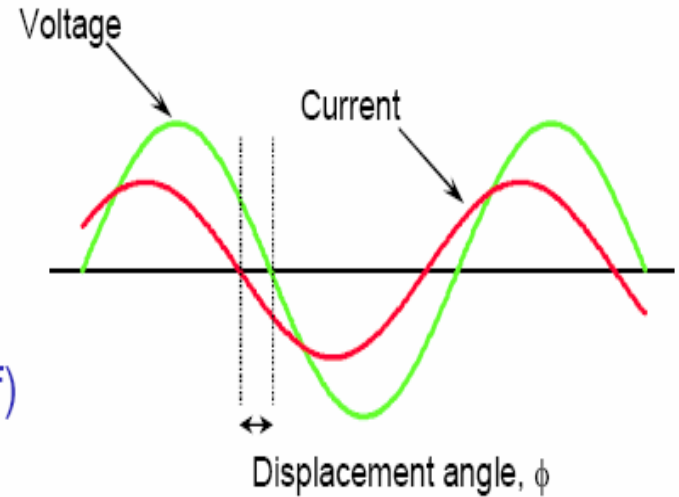
Apparent power:

$$S = \text{Voltage} * \text{Current}$$

Active power:

$$P = \text{Voltage} * \text{Current} * \cos(\phi)$$

$$\text{Displacement Power Factor} = \cos(\phi)$$



# True power factor watts

True Power Factor defined as the ratio of the Active Power to the Apparent Power:

$$I = (V \times I_1 \times \cos(\phi)) / (V \times I_{RMS})$$

$$I = (I_1 \times \cos(\phi)) / I_{RMS}$$

For VFDs in general True Power Factor:

$$I \approx I_1 / I_{RMS} \quad (\text{as } \cos(\phi) \approx 1)$$



# THID: Total Harmonic (I) current Distortion

- A measurement of the harmonic performance of a product
- Each individual harmonic current ( $I_n$ ) can be represented as a percentage of the fundamental  $I_1$ :
  - e.g. 5<sup>th</sup> harmonic current =  $(I_5/I_1) \times 100\%$
- As each harmonic current can be out of phase with other harmonic currents, to produce a total sum of the harmonic currents, they have to be added vectorially (take the square root of the sum of the square of each ratio for each relevant harmonic!):

$$THID = \sqrt{\sum_{n=2}^{n_{\max}} \left( \frac{I_{(n)}}{I_{(1)}} \right)^2} \cdot 100\%$$

# THVD: Total Harmonic Voltage Distortion

- A measurement of the harmonic performance of a system
- Each individual harmonic voltage ( $V_n$ ) resulting from each harmonic current ( $I_n$ ) passing through the transformer's impedance ( $Z_n$ ) can be calculated by:
  - $V_n = I_n \times Z_n$  (remember the impedance increases with frequency)
- These harmonic voltages can then be represented as a percentage of the fundamental/nominal voltage  $V_{nom}$ :
  - e.g. 5<sup>th</sup> harmonic voltage =  $V_n / V_{nom} \times 100\%$
- Again to get the total harmonic voltage distortion these need to be added vectorially:

$$THVD = \sqrt{\sum_{n=2}^{n_{max}} \left( \frac{V_{(n)}}{V_{(1)}} \right)^2} \cdot 100\%$$



# VOLTAGE HARMONIC LIMITS AS PER IEEE 519-1992

	<b>SPECIAL APPLICATION</b>	<b>GENERAL SYSTEM</b>	<b>DEDICATED SYSTEM</b>
THD (Voltage)	<b>3%</b>	<b>5%</b>	<b>10%</b>



# TDD: Total Demand Distortion (IEEE-519:1992)

Total Demand Distortion equals harmonic distortion as a percentage of maximum demand load current (15 or 30 min demand)

$$THD = \sqrt{\sum_{n=2}^{n_{\max}} \left(\frac{I_{(n)}}{I_{(L)}}\right)^2} \cdot 100\% \quad TDD = \frac{1}{I_L} \sqrt{\sum_{n=2}^{n_{\max}} I_{(n)}^2} \cdot 100\%$$

Thus, TDD is a system level parameter as it depends upon the definition of  $I_L$ . The definition of  $I_L$  is crucial to this parameter.  $I_L$  is the maximum load current at the PCC (i.e. total current from all loads) (e.g. total load current on transformer)

This can be very different to THD

IEEE 519:1992 suggests the following limits for TDD:



# IEEE-519 Current Distortion (THID) limits for General Distribution Systems

120 V – 6900 V (Table 10.3 under “Recommended Practices for Individual Consumers”)

$I_{SC}/I_L$	<11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0 *
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

TDD = THID for more than 15 min. or 30 min.

$I_{SC}$  = maximum short circuit current at PCC

$I_L$  = maximum fundamental load current at PCC

\* Limit for all power generation equipment



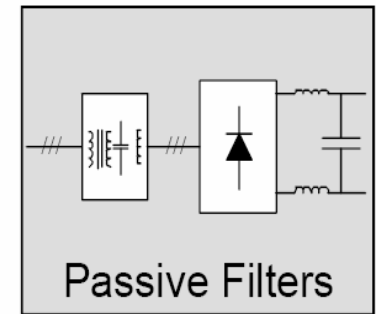
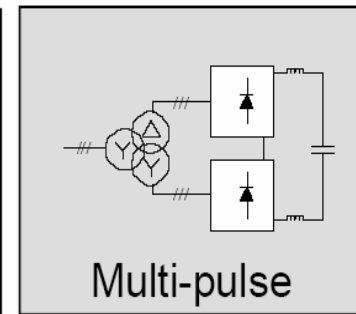
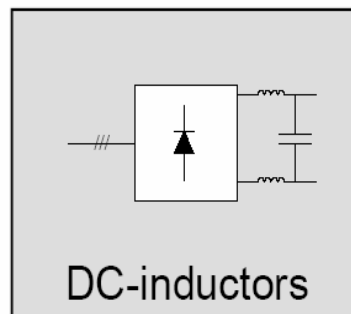
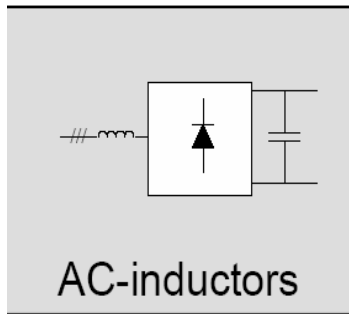
# IEEE-519

- PCC
  - At point of metering
  - Point where nonlinear load meets linear loads
- TDD
  - THID for 15 or 30 minutes
- THD
  - Instantaneous value of harmonic distortion
  - THVD Instantaneous value of harmonic Voltage distortion
  - THID Instantaneous value of harmonic current distortion

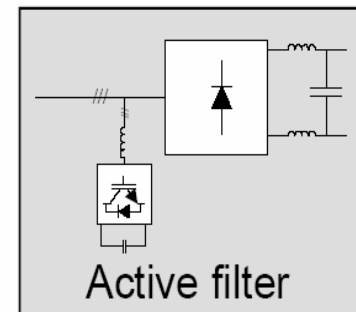
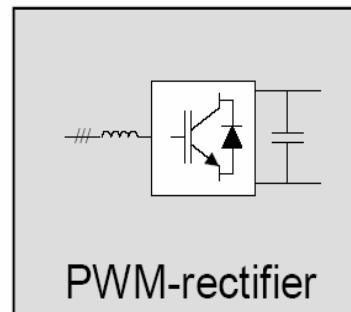


# Techniques to reduce VFD Harmonics

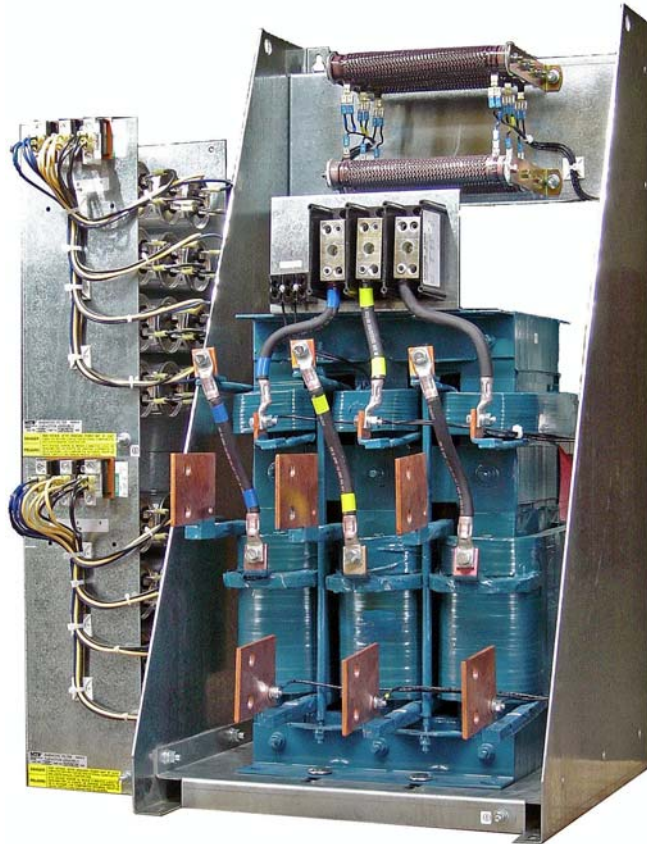
## Passive



## Active



# Matrix™ Harmonic Filters



**The High Performance  
Low Cost Alternative  
to 12-pulse and 18-  
pulse Drives**

# Matrix Harmonic Filters

- **A Matrix Harmonic Filter feeding a 6-pulse drive provides better performance than 12-pulse and 18-pulse drives**
  - Lower cost
  - Smaller size
- **Help VFDs meet international power quality standards for harmonic distortion**
  - IEEE- 519, G5/4, AS2279
  - EN 61000-3-2, EN 61000-3-4



## Matrix Filters Offer ...

- ***Guaranteed THID levels of 5%***
- **High Efficiency**
- **Superior harmonic mitigation performance**
  - Better than 12-pulse drives
  - Better than 18-pulse drives
  - **Better than tuned harmonic trap filters**
- **No power system resonance problems**
- **No extensive harmonic studies**
- **IEEE – 519 compliance**

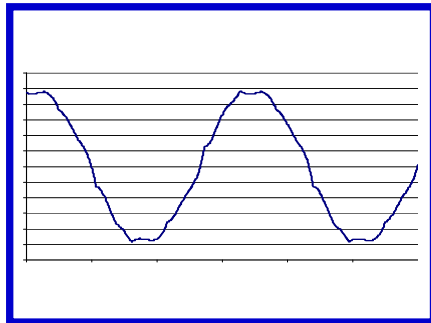


# Matrix Filter Suitability

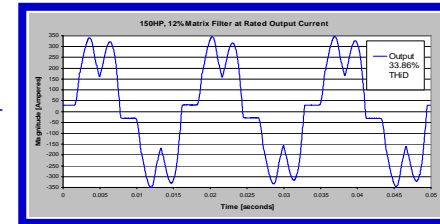
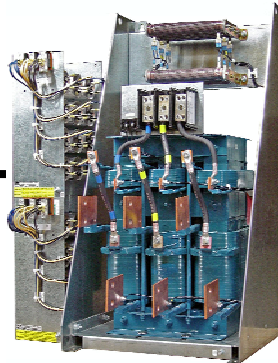
- Diode or SCR front end
  - Including *phase control*
  - Including SCR pre-charge circuits
- AC or DC drives
- VFD w/ DC link choke or AC line reactor
- Constant or Variable Torque

**Application Notes available for special applications**

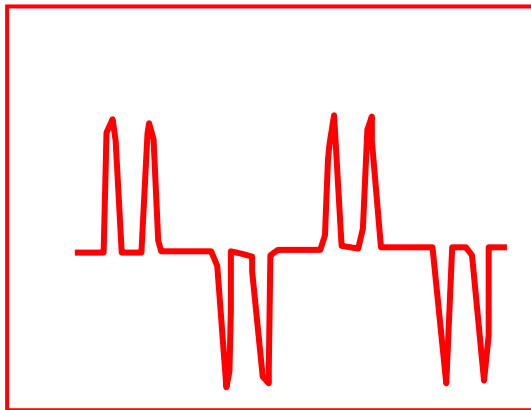
# Matrix Filters Achieve the Cleanest Input Power



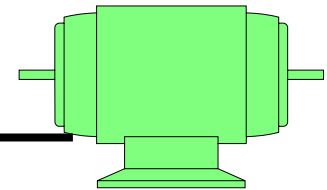
With Matrix Filter



Without Matrix Filter

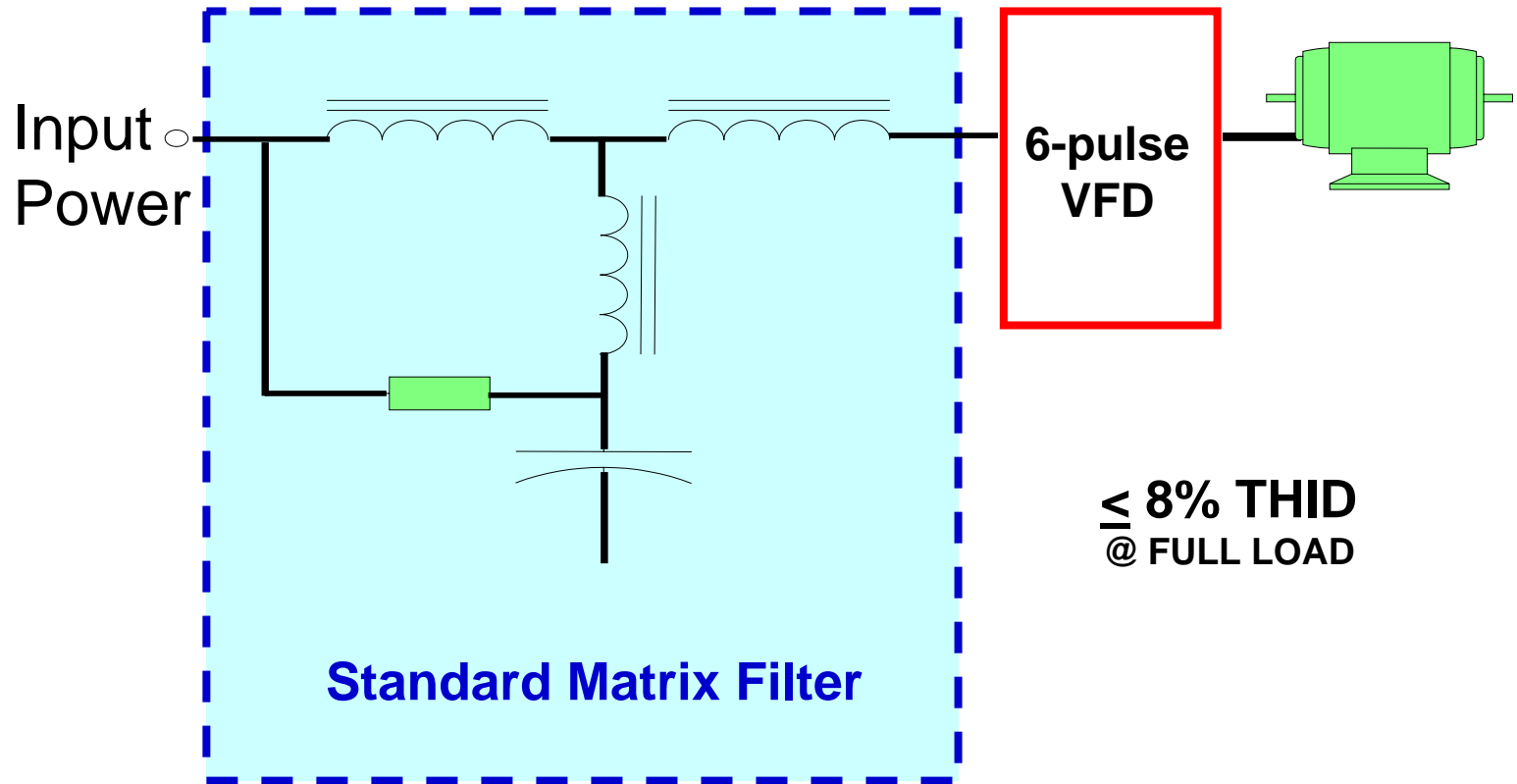


Standard  
6-pulse  
VFD

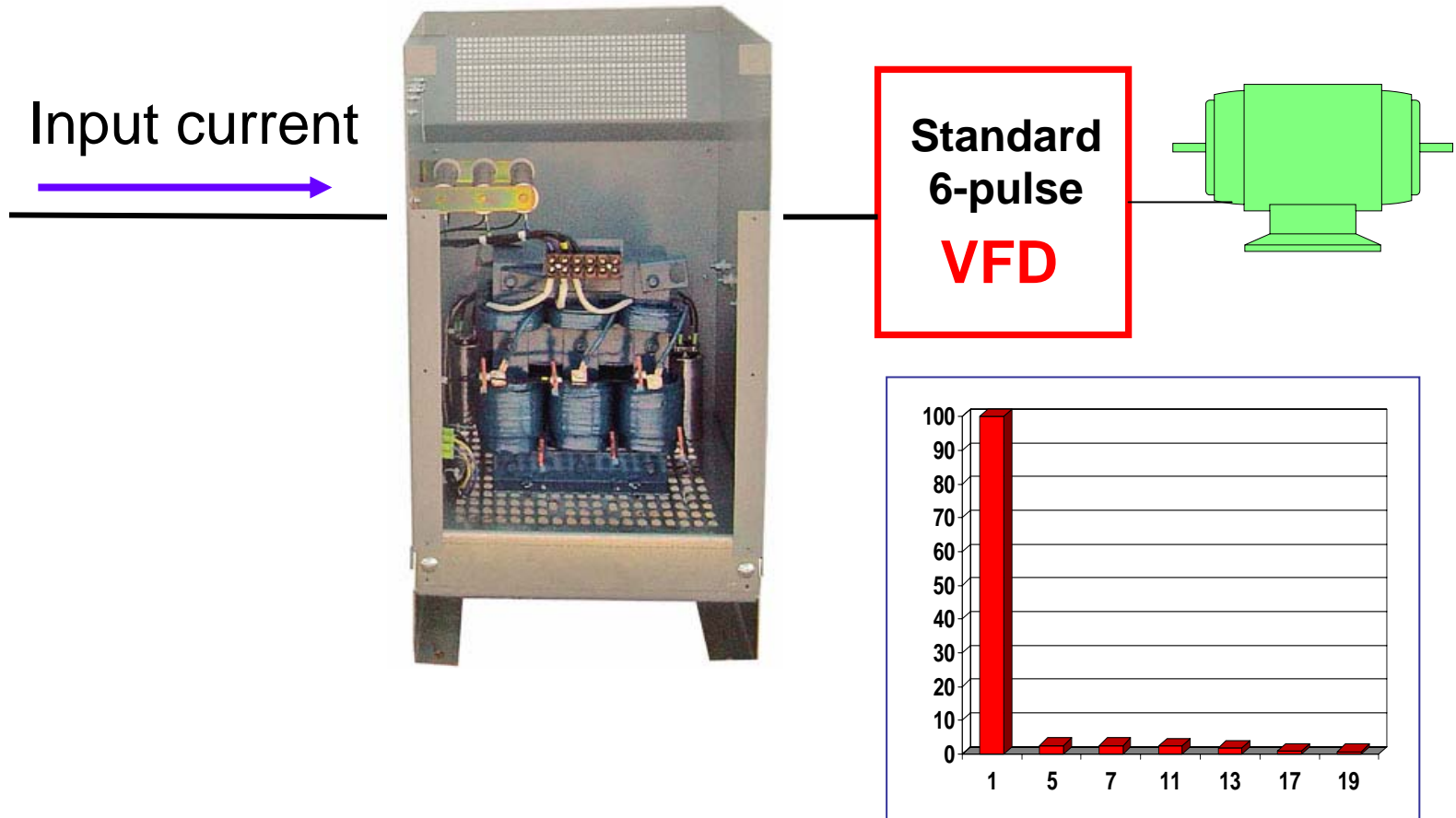


Matrix – They're *LOW PASS* harmonic filters so they filter all harmonic frequencies

# Matrix Filter Circuit Configuration



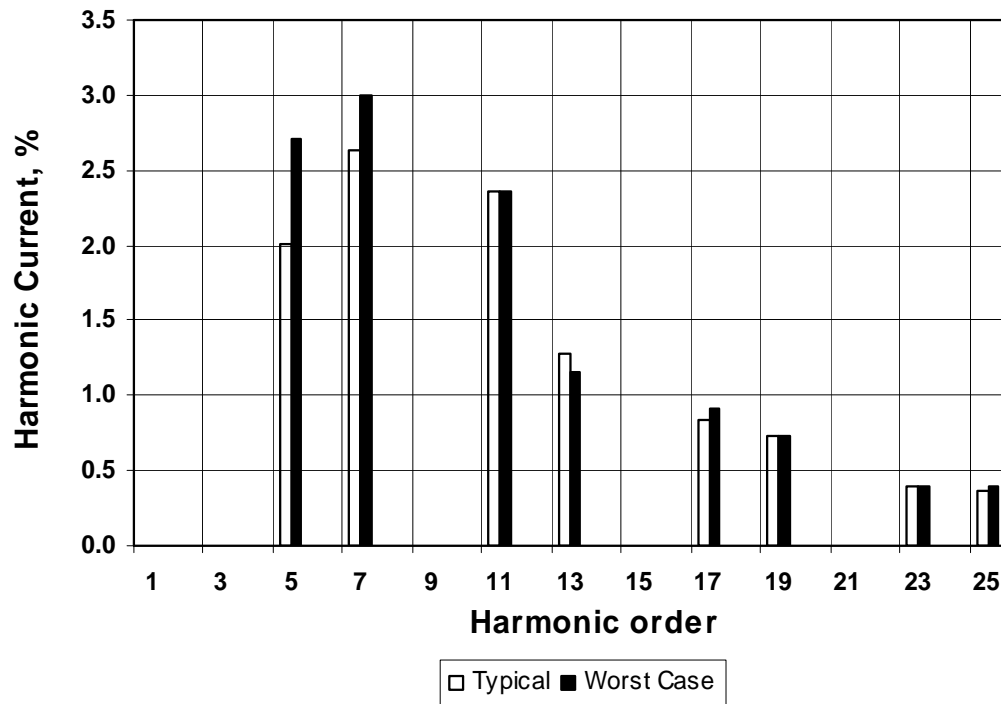
# 5% Matrix Filters reduce input current Harmonic Distortion even better than 18-pulse drives



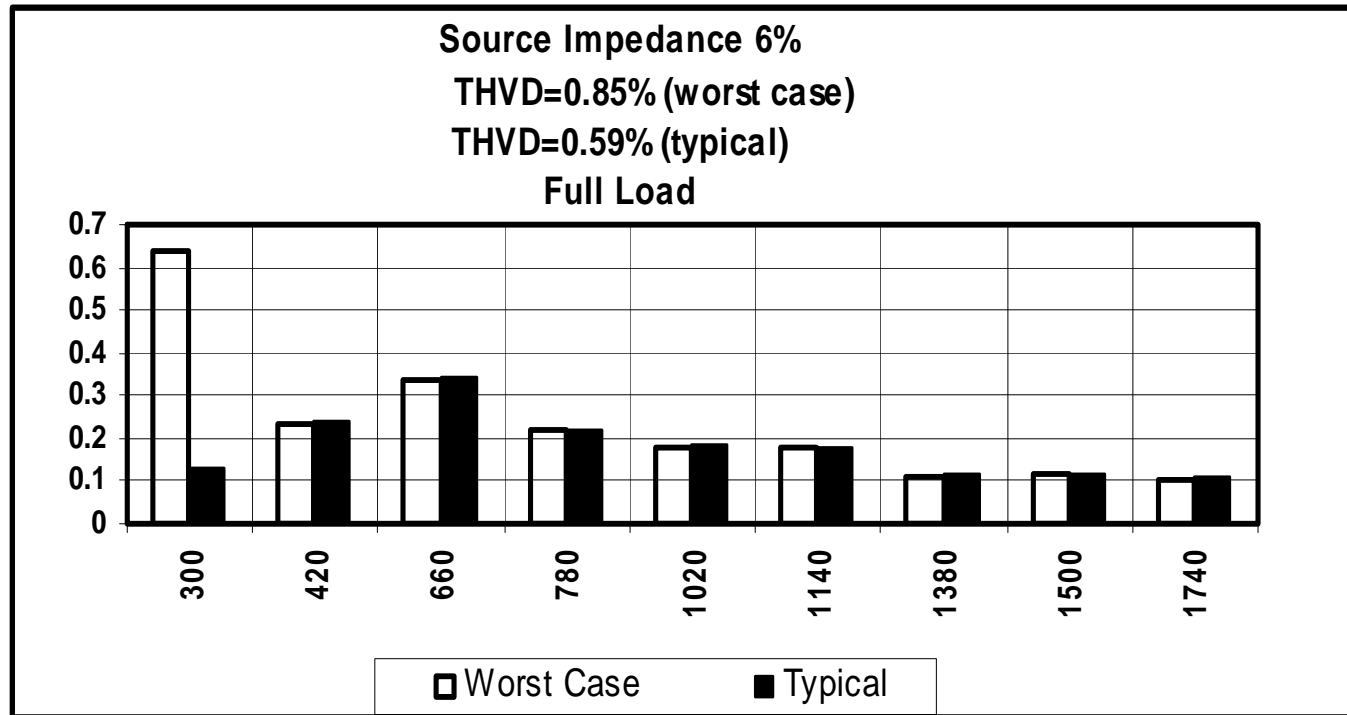
# Harmonic Current Spectrum

## 5% Matrix Filter

5% Matrix Filter Harmonic Spectrum  
100% Load



# 5% Matrix Filter Typical Harmonic Voltage Distortion 6% Source Impedance

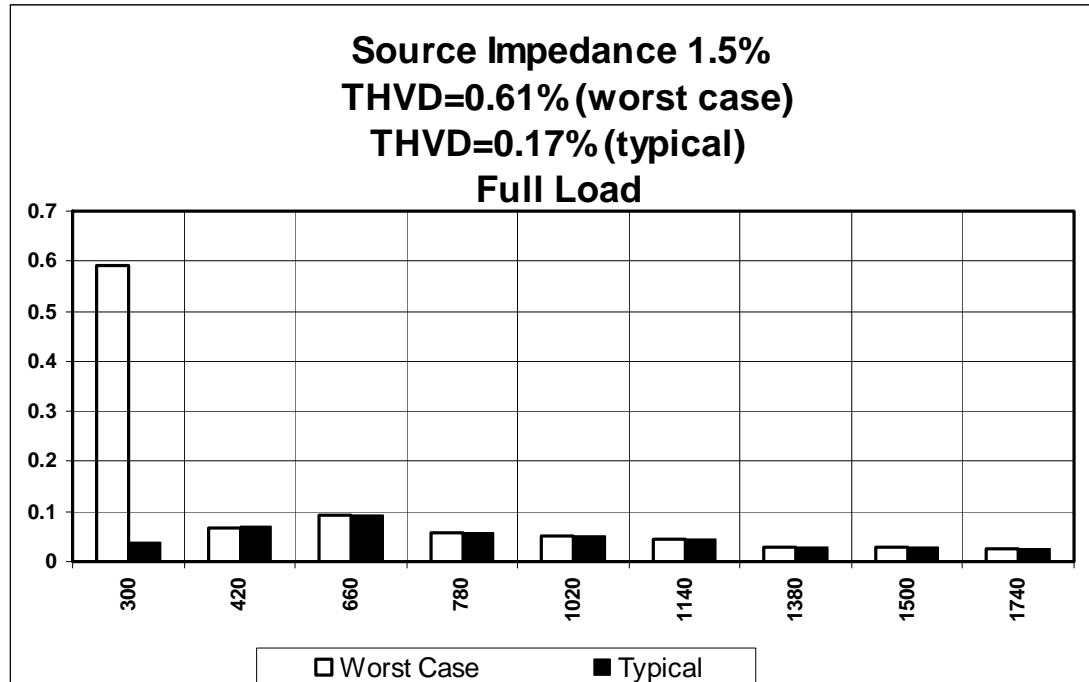


IEEE-519 limits are 3% Individual, **5% THVD**

# 5% Matrix Filter

## Typical Harmonic Voltage Distortion

### 1.5% Source Impedance



IEEE-519 limits are 3% Individual, **5% THVD**

## IEEE - 519 Voltage Distortion Limits –

(Table 10.2 under “Recommended Practices for Individual Consumers/Limits on Commutation Notches”)

Low-Voltage System Classification and Distortion Limits			
	Special Applications*	General System	Dedicated System†
Notch Depth	10%	20%	50%
THD (Voltage)	3%	5%	10%
Notch Area ( $A_N$ )‡	16400	22,800	36500

**NOTE:** The Value  $A_N$  for other than 480 V systems should be multiplied by  $V/480$

\* Special applications include hospitals and airports.

† A dedicated system is exclusively dedicated to converter load.

‡ In volt-microseconds at rated voltage and current.

# IEEE - 519 Voltage Distortion Limits – (Table 11.2 under “Recommended Practices for Utilities”)

Voltage Distortion Limits		
Bus Voltage at PCC	Individual Voltage Distortion %	Total Voltage Distortion THD (%)
69kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

**NOTE:** High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will be attenuated by the time it is tapped for a user.

# Harmonic Voltage Distortion

$$\text{THVD} = \frac{\sqrt{\sum_{h=2}^{\infty} (V_h)^2}}{V_1} \cdot 100\%$$

## Where:

- $V_h$  = magnitude of individual harmonic content (RMS volts)
- $h$  = harmonic order
- $V_1$  = fundamental Voltage (RMS )

## and Ohm's Law works

$$\text{THVD} = \frac{\sqrt{\sum_{h=2}^{\infty} (hX_1 I_h)^2}}{V_1} \cdot 100\%$$

Where:

- $I_h$  = magnitude of individual harmonic content (RMS amps)
- $h$  = harmonic order
- $X_1$  = fundamental reactance
- $V_1$  = fundamental voltage (RMS)

# Which can be reduced to:

$$\text{THVD} = \frac{\sqrt{\sum_{h=2}^{\infty} (hI_h)^2}}{I_{sc}} \cdot 100\%$$

Where:

- $I_h$  = magnitude of individual harmonic content (RMS amps)
- $h$  = harmonic order
- $V_1$  = fundamental current (RMS amps)

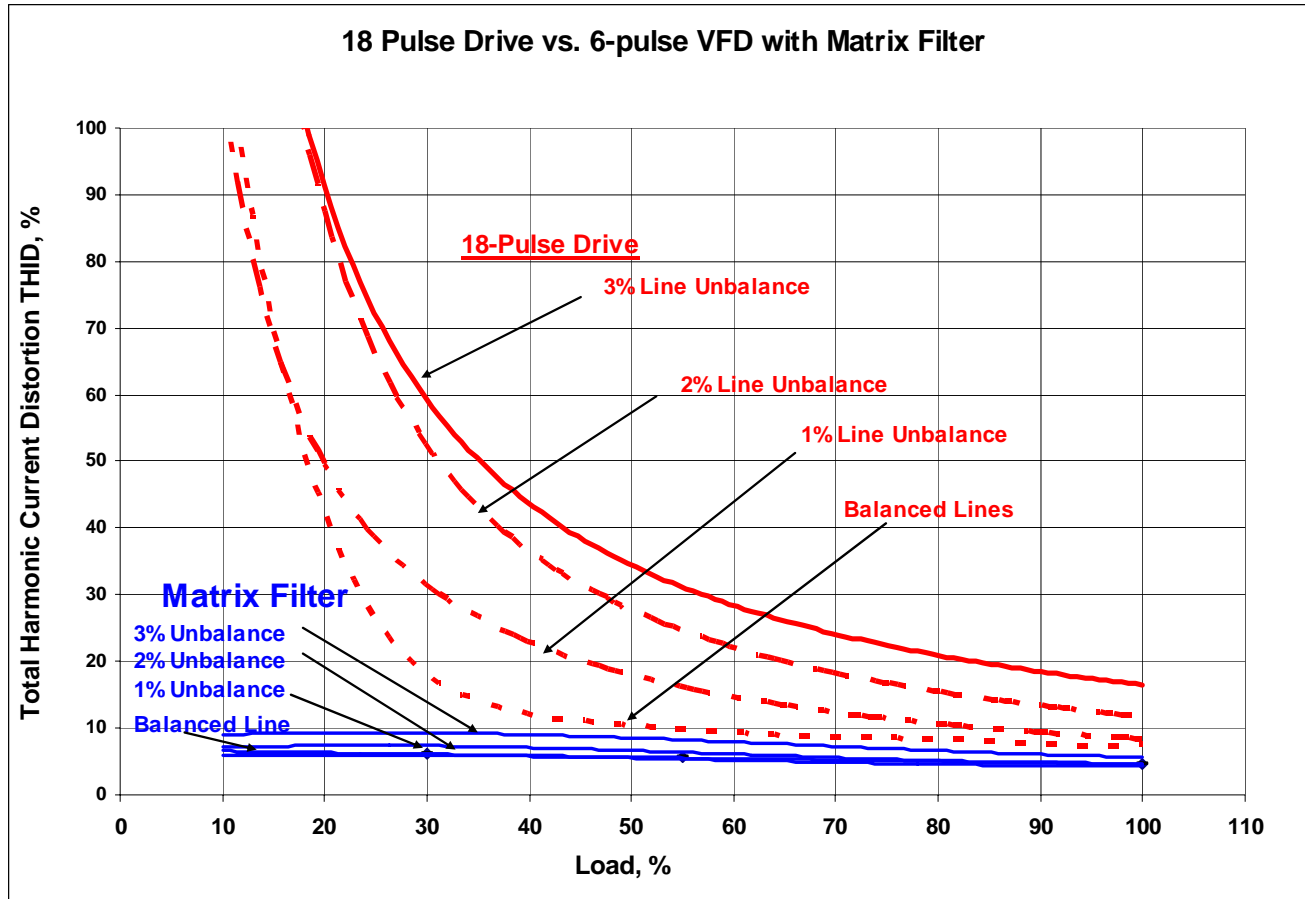
# Voltage Unbalance.....

ANSI Standard C84.1-1989 Reports that at the PCC:

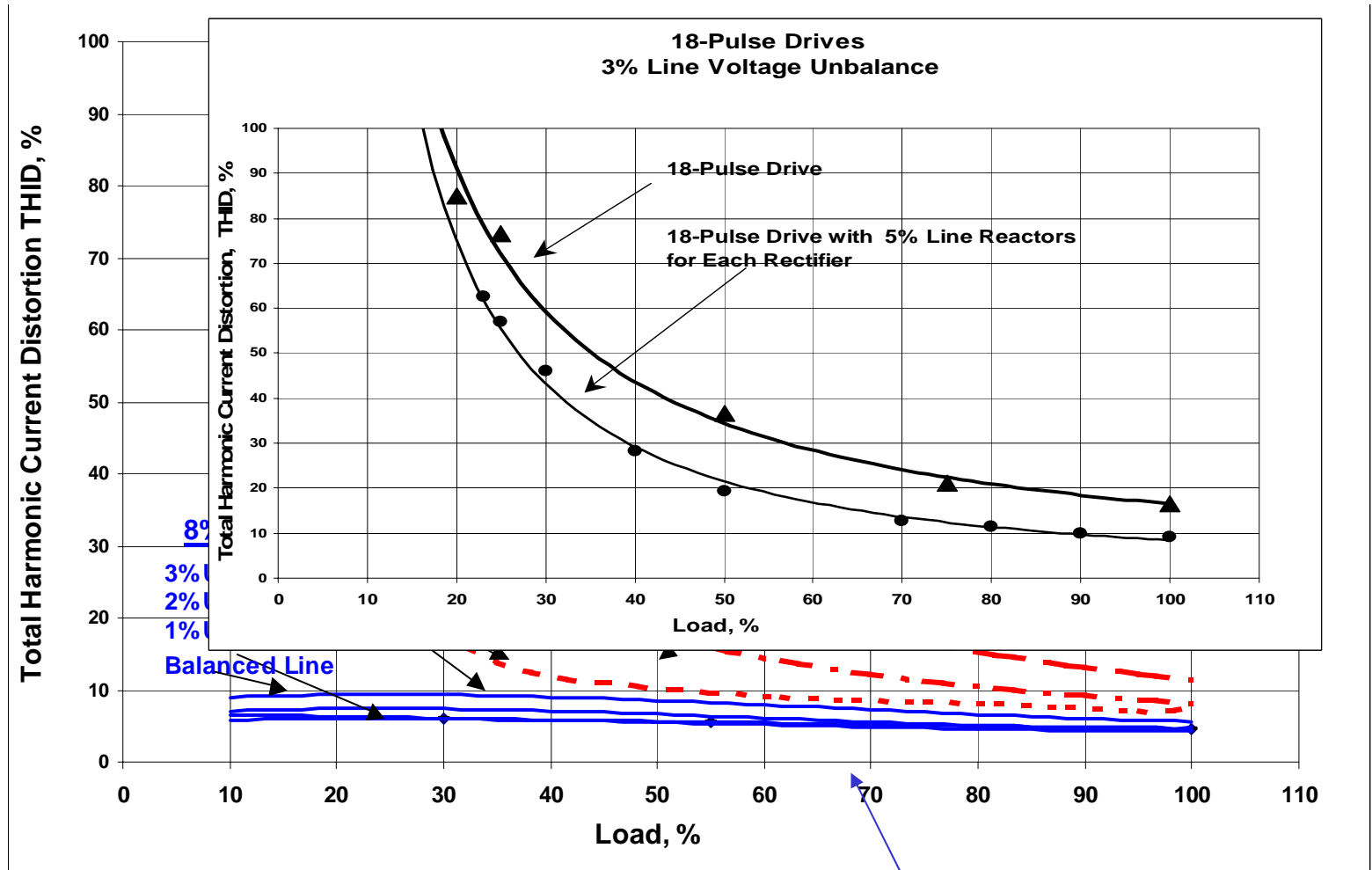
- 98% of power systems are within 0 - 3%
- 66% of power systems are within 0 - 1%
  - 34% of systems are 1% to 3% unbalanced
- *Load unbalance within the building power distribution system adds to the utility unbalance at the point of utilization.*



# 6-pulse VFD with 5% Matrix Filter performs better than 18-pulse drive under *normal operating conditions* (0% to 100% load, with voltage unbalance)



# 5% Matrix Filters are even better than 18-pulse VFD with additional reactors



Matrix (from previous chart)

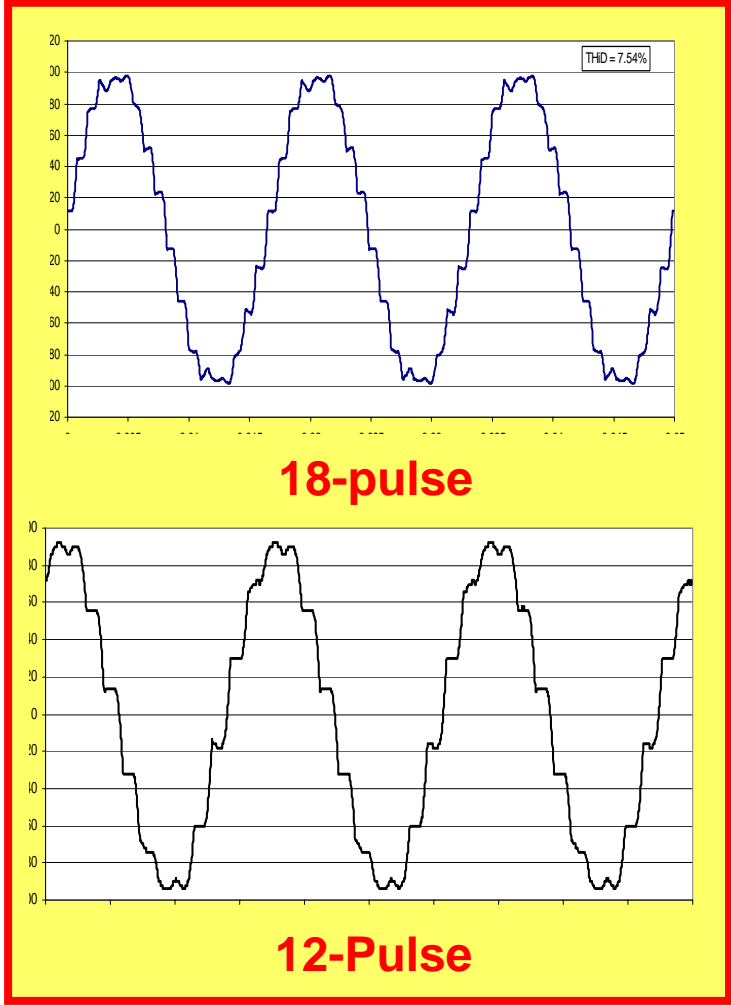
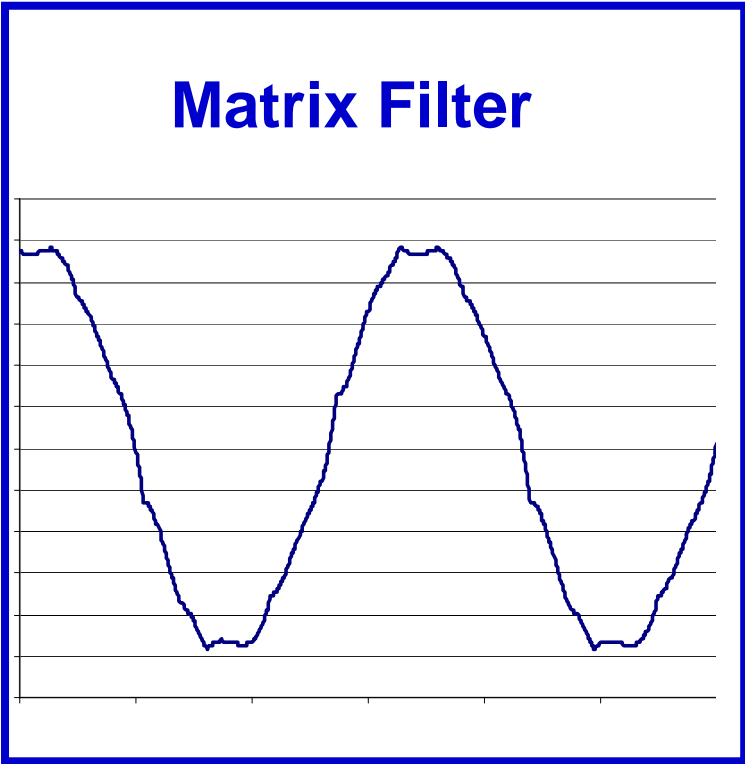


# IEEE – 519 Solutions

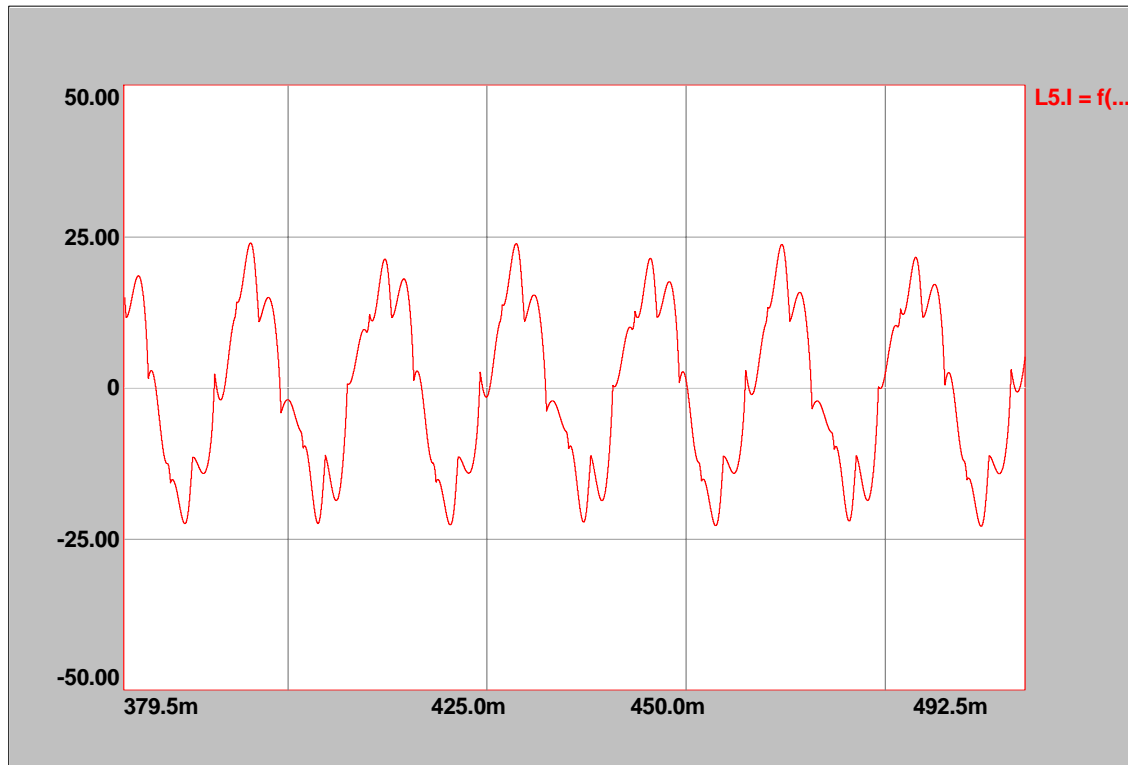
Desired % THID at PCC (IEEE-519)	3% Line Reactor	5% line Reactor	5% Line + 3% DC Reactors	8% Matrix Filter (M8)	5% Matrix Filter (M5)
	% Maximum AFD Load if all AFDs use same Harmonic Mitigation Method				
5	11	14	18	62	100
8	18	23	29	100	100
12	27	34	43	100	100
15	34	43	54	100	100
20	45	57	71	100	100



# Matrix Filters produce cleaner input current waveforms than multi-pulse drives



# 5<sup>th</sup> Harmonic Trap Input Current



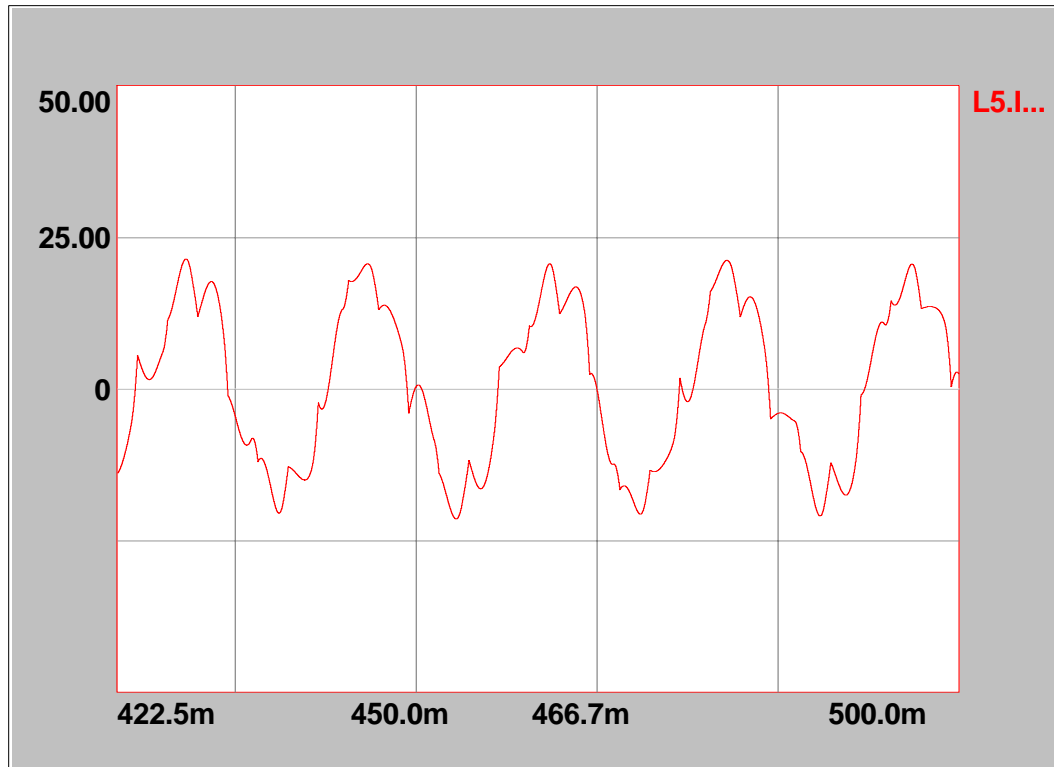
**Input Current  
THID: 24.35%**

**Load: 100% Input Voltage: balanced Line Impedance: 0.25%**

**Input Reactor: 5% Output Reactor: None**



# Input Current – Enhanced 5<sup>th</sup> Harmonic Trap (w/AFD input reactor)



**Input Current  
THID: 23.07%**

**Load: 100%    Input Voltage: balanced    Line Impedance: 0.25%**  
**Input Reactor: 5%    Output Reactor: 1.5%**



# Matrix Filters are better than other Low Pass Filters

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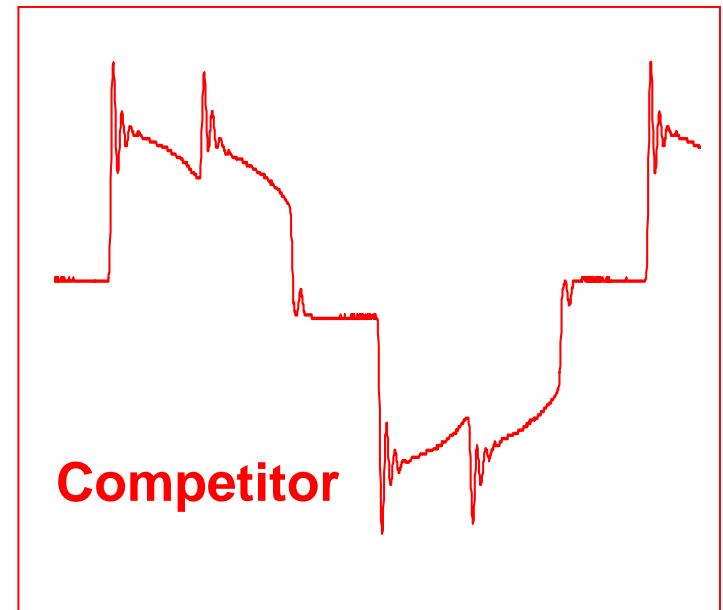
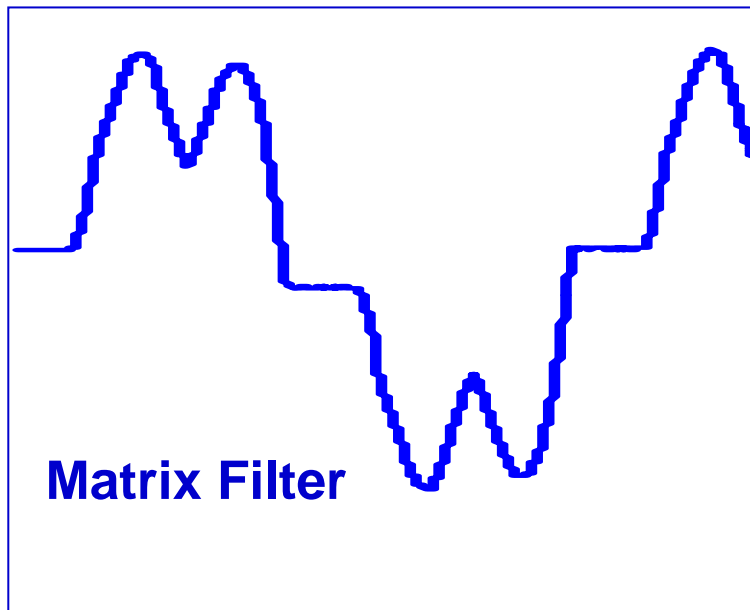
- Guaranteed performance levels
- Better current waveform to the drive
- Use with or without SCRs, input reactors & bus chokes



# Matrix Filters deliver better VFD input current waveform than **Competitor's Low Pass Filter**

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VFD input current waveforms



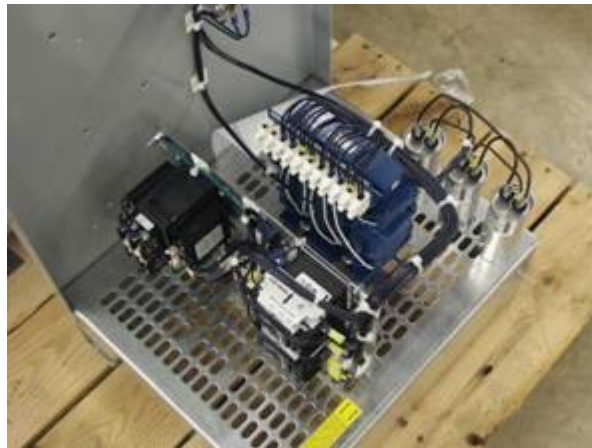
# Matrix Harmonic Filters 6 – 1200 Amps Standard 208 – 690 VAC, 50/60 Hz



# Enclosure Options for Outdoor and Marine Environments



# Custom Engineered Matrix Harmonic Filters



Any Voltage, any Frequency,  
Any package thru 1800 Amps

Visit MTE online [www.mtecorp.com](http://www.mtecorp.com) and try "CLICK find" for product selections and data

The screenshot shows the MTE Corporation website in a Windows Internet Explorer browser. The page features a blue header with the MTE logo and navigation links. The main content area is titled "Welcome to MTE Corporation" and includes a paragraph about the company's products. Below this, there are several product categories, each with a list of items and a "CLICK find" button:

- Power Surges affecting Inverter Drives**
  - Line/Load Reactors
  - 3-Phase Reactor with Surge Arrestor
  - DC Link Chokes
  - Surge Arrestors
  - Matrix Harmonic Filters
- Harmonics from Power Electronics**
  - Matrix Harmonic Filters
  - Line/Load Reactors
  - DC Link Chokes
  - 3rd Harmonic Filters
- Motor Protection**
  - Sine Wave Motor Protection Filters
  - Dv/dt Motor Protection Filters
  - Line/Load Reactors
- EMI/RFI noise suppression**
  - RF/EMI Filters
  - Noise Suppression Network

A callout box on the right side of the page reads: "Web site. Your International Power Quality Resource! New Matrix D Harmonic filters now".

At the bottom left, the "WORLD HEADQUARTERS" address is listed: "an SL Power Electronics Company, N63 W13330 Leon Dr., Menomonee Falls, WI 53051 USA".

The bottom right corner contains a search bar and a "Subscribe" form.

# Use "CLICK find" for Matrix Filters selection, price, CAD, user manuals and brochures

**MTE Matrix series D Filters**  
Product Configuration Assistant

Enter the order code for the desired MTE Matrix series D Filters...

MDP0240D

Click make the selections for the product that you need using the interactive selection chart.

Accept Validate Cancel Reset Undo Redo

FILTER DATA	
Enclosure	Panel Mount
Voltage	480V 60 Hertz
Motor Selection	200 HP
Filter Amps	240 Amps

ADDITIONAL INFORMATION	
Watts	0 Watts
Terminal Wiring AWG	2 - 0000
Terminal Torque	50
Weight	298 Lbs

Motor Selection

- 3 HP
- 5 HP
- 7.5 HP
- 10 HP
- 15 HP
- 20 HP
- 25 HP
- 30 HP
- 40 HP
- 50 HP
- 60 HP
- 75 HP
- 100 HP
- 125 HP
- 150 HP
- 200 HP
- 250 HP
- 300 HP
- 400 HP
- 500 HP
- 600 HP
- 700 HP
- 800 HP
- 900 HP
- 1000 HP

MESSAGE

# MTE

AN SL POWER ELECTRONICS COMPANY

