LISTEN.
THINK.
SOLVE.SM

Harmonic Mitigation for Variable Frequency Drives

HWEA Conference
February 15, 2011

Kelvin J. Hurdle
Rockwell Bus. Dev. Mgr.

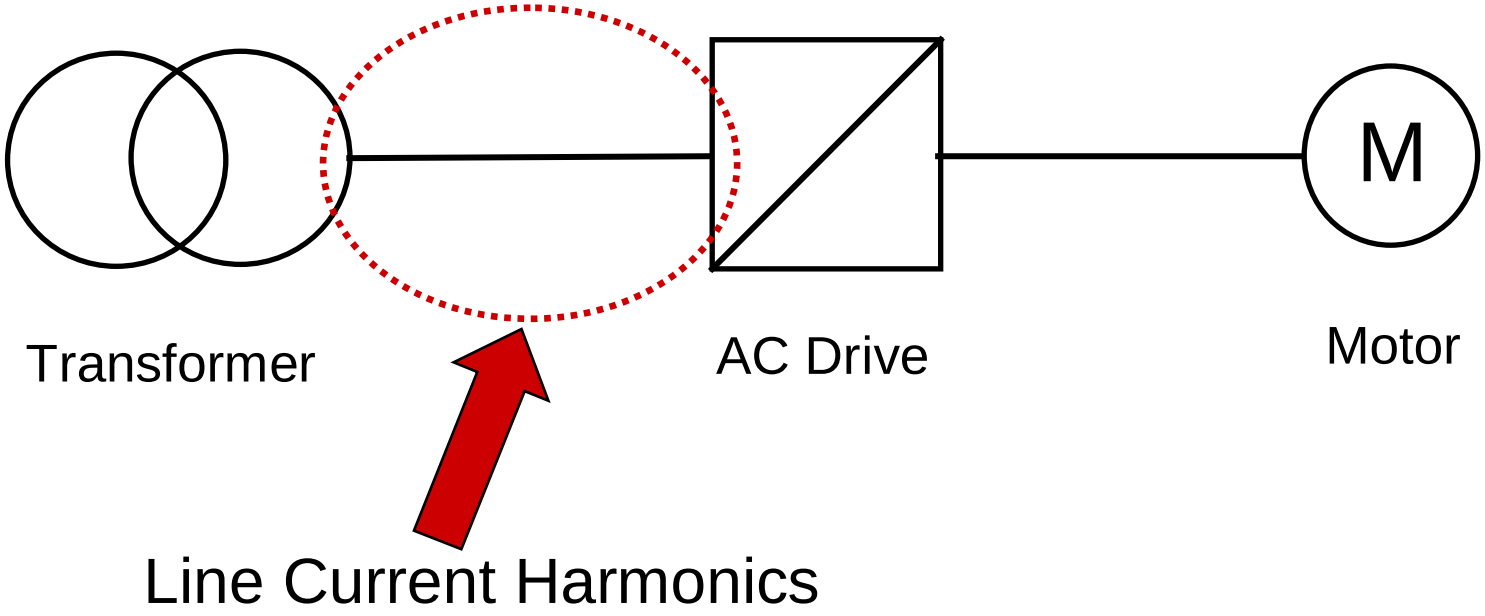
ALLEN-BRADLEY • ROCKWELL SOFTWARE • DODGE • RELIANCE ELECTRIC

Rockwell Automation

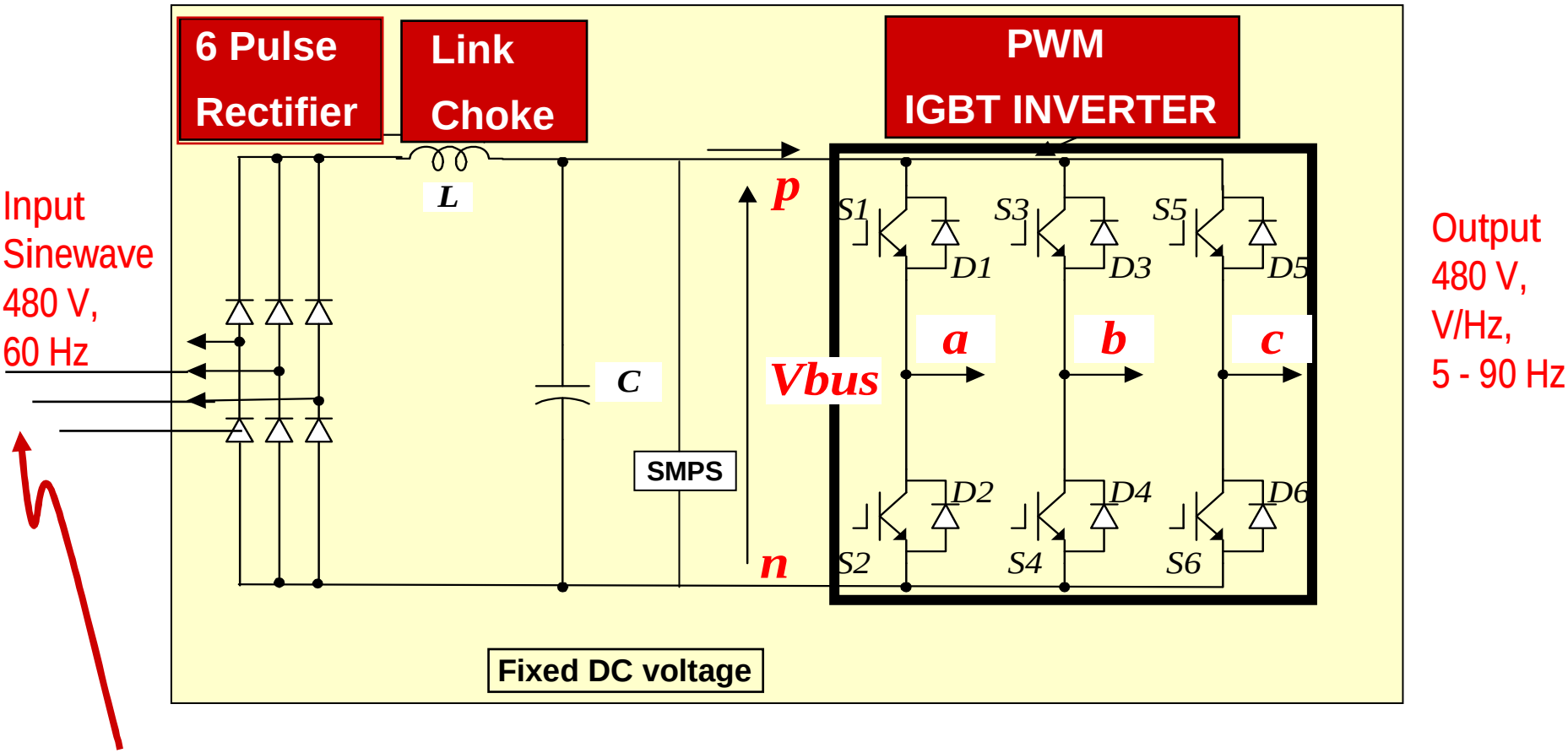
OVERVIEW

- Linear vs. Non- Linear Load Definitions
- AC Drive Input Current Harmonics
- Potential Affects of Harmonics
- Application of Harmonic Industry Standards, IEEE Std. 519-1992
- Harmonic Mitigation Techniques

Drive System

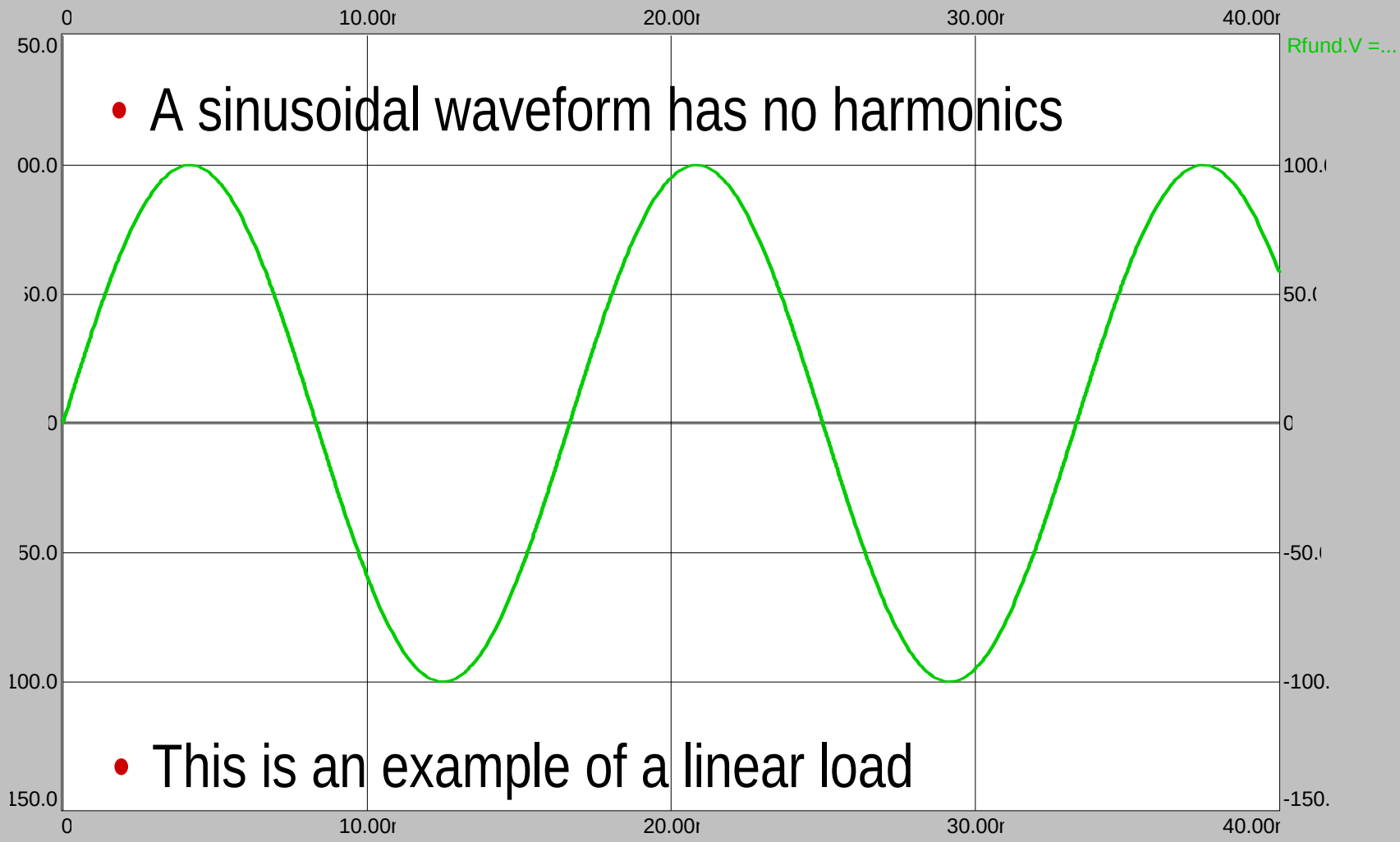


PWM AC Drive with 6-Pulse Rectifier



Utility Input current to a 6-pulse rectifier is non-sinusoidal and produces current harmonics which flow back into the power system

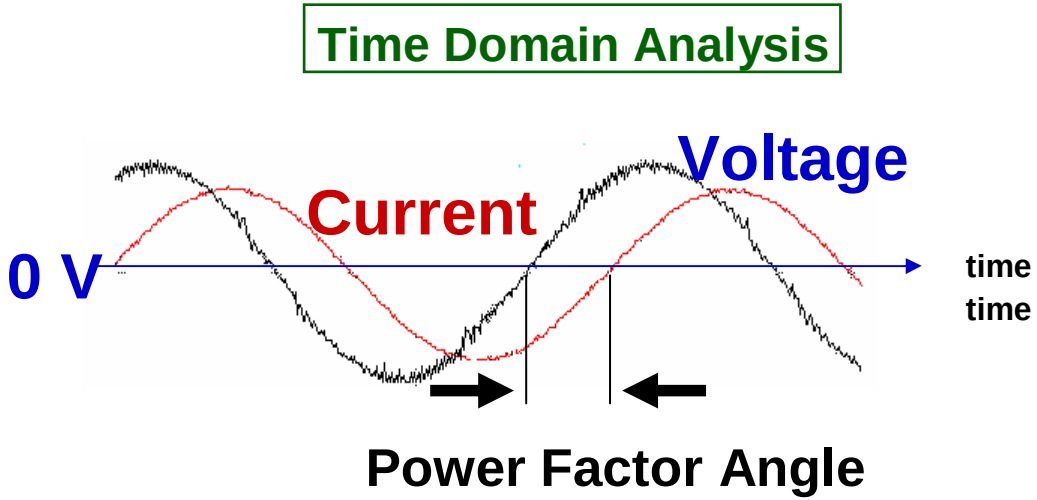
What are Harmonics?



What is a Linear Load?

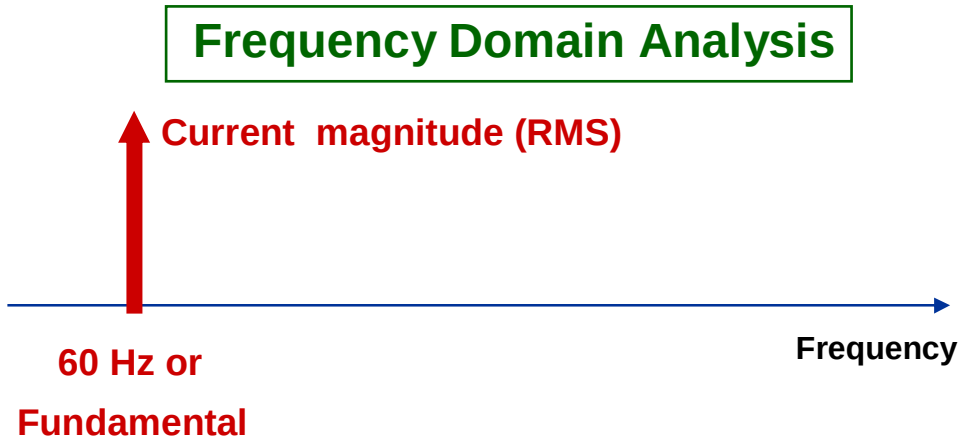
Linear Load:

Current waveshape linearly follows the Utility sinewave Voltage waveform
Current can differ in magnitude & power factor phase angle

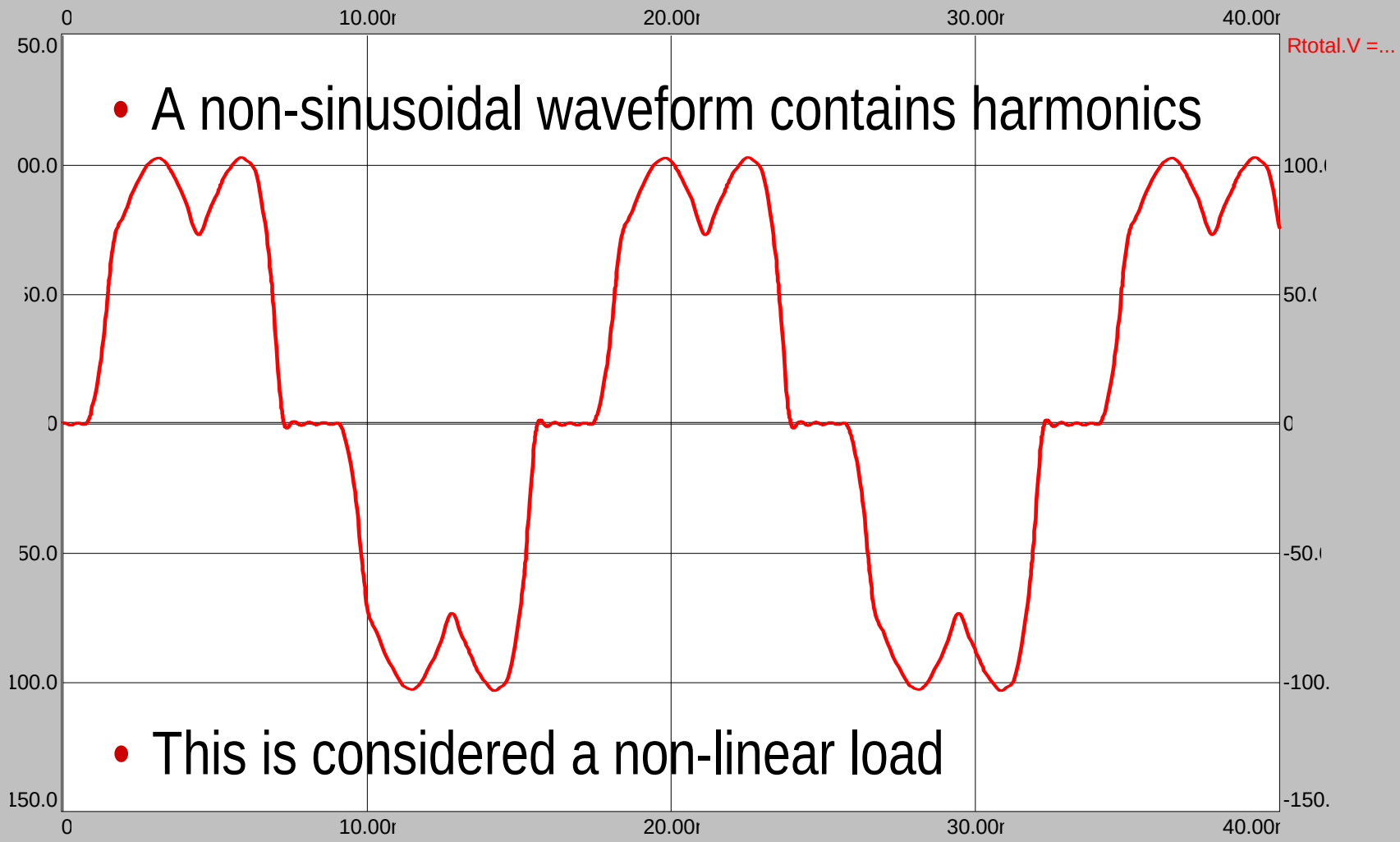


Linear Commercial Loads:

- Induction motors
- Incandescent lights
- Resistance heaters
- Electromagnetic devices
- Transformers
  (non-linear with over-voltage)



What are Harmonics?



What is a Non-Linear Load?

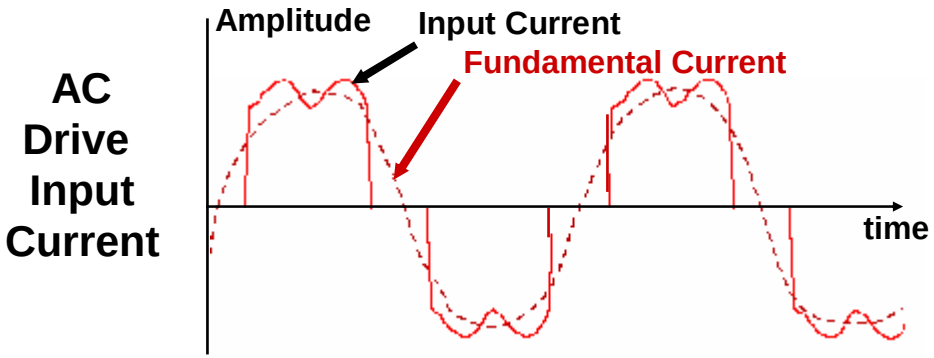
Harmonics are .....

Deviations from the Ideal Fundamental AC line voltage and current waveforms

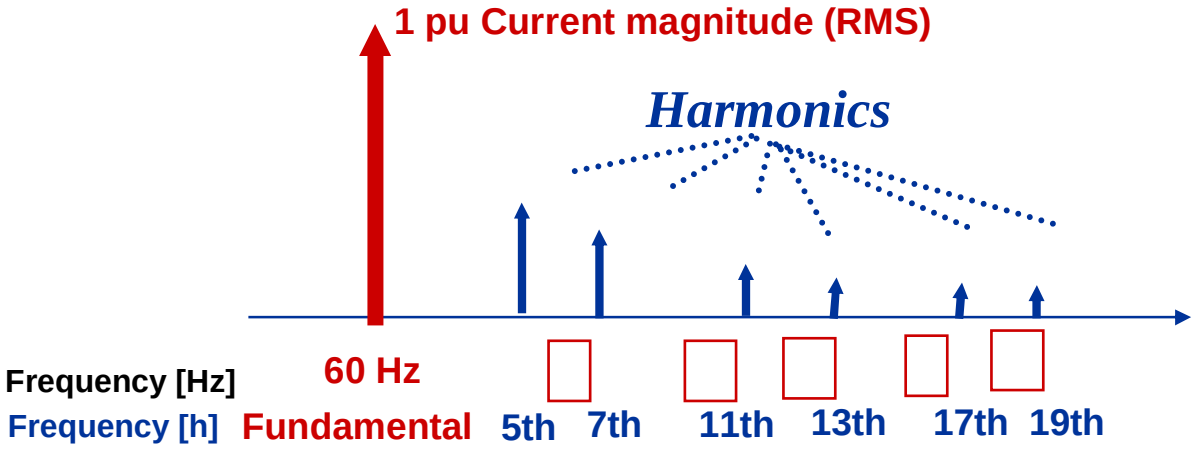
Non-linear loads contain .....

Current Harmonics which cause *Voltage Harmonic* problems for other users

Time Domain Analysis



Frequency Domain Analysis



Root Cause of Problems with Other Equipment

Current Harmonics

create

Voltage Distortion

Power Consumer Issues Associated with non-Linear Loads

Non-linear Commercial loads generally come from:

- Fluorescent lights
- Computers and CRT's
- Fax machines
- And other single phase office equipment

Non-linear Industrial loads generally come from:

- Welders
- Arc furnaces
- UPS and DC power supplies
- DC Drives & AC Drives

* Fastest growing factory related non-linear load issue is with AC drives
* This is due to the ever increasing number of installations

What problems do they cause?

- Increased Utility current requirement — inability to expand or utilize equipment
- Component overheating — distribution transformers & wires
- Nuisance tripping causing lost productivity — sensitive equipment
- Equipment malfunction — due to multiple or loss of zero crossing
- Noise transfer to other loads — possibly even other utility customers
- Incorrect meter readings, relays malfunction — maintenance time
- Communication or Telephone Interference problems
- Excitation of Power System Resonance's creating over-voltage’s
- Voltage Flat Topping Problem

Effects of Harmonics on Power System?

- How are harmonics and power factor related?
  - Harmonics increase the required current supplied
  - Results in increased power requirement from the utility
  - If the total load uses all the utility supplied power, the distribution system is called unity, or 1.0 power factor.
  - If the same load requires more utility supplied power due to harmonics or other losses, then the power factor decreases.
  - Some power utilities may impose penalties to the user if they oversize their distribution system due to a poor power factor.

Effect of Harmonics on the Power System?

- How do I determine when I will have a Harmonics Issue with my new or existing Drive Installation ?
- Drives are part of the Non-Linear Load
- If the Non-Linear Load is SIGNIFICANTLY higher than the Linear Load, there is a potential for Harmonic Distortion problems

Effect of Harmonics on the Power System?

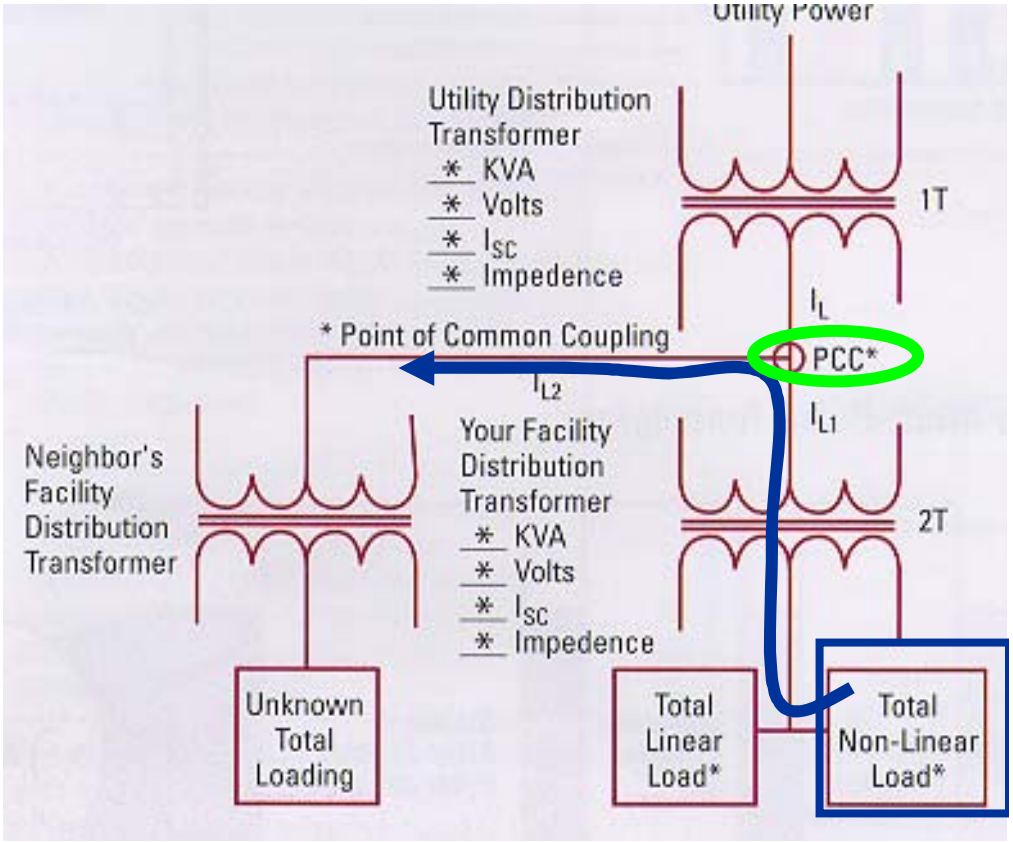
Harmonic Currents flowing through the system

Produce Voltage Distortion at various Points of Common Coupling (PCC) with other loads

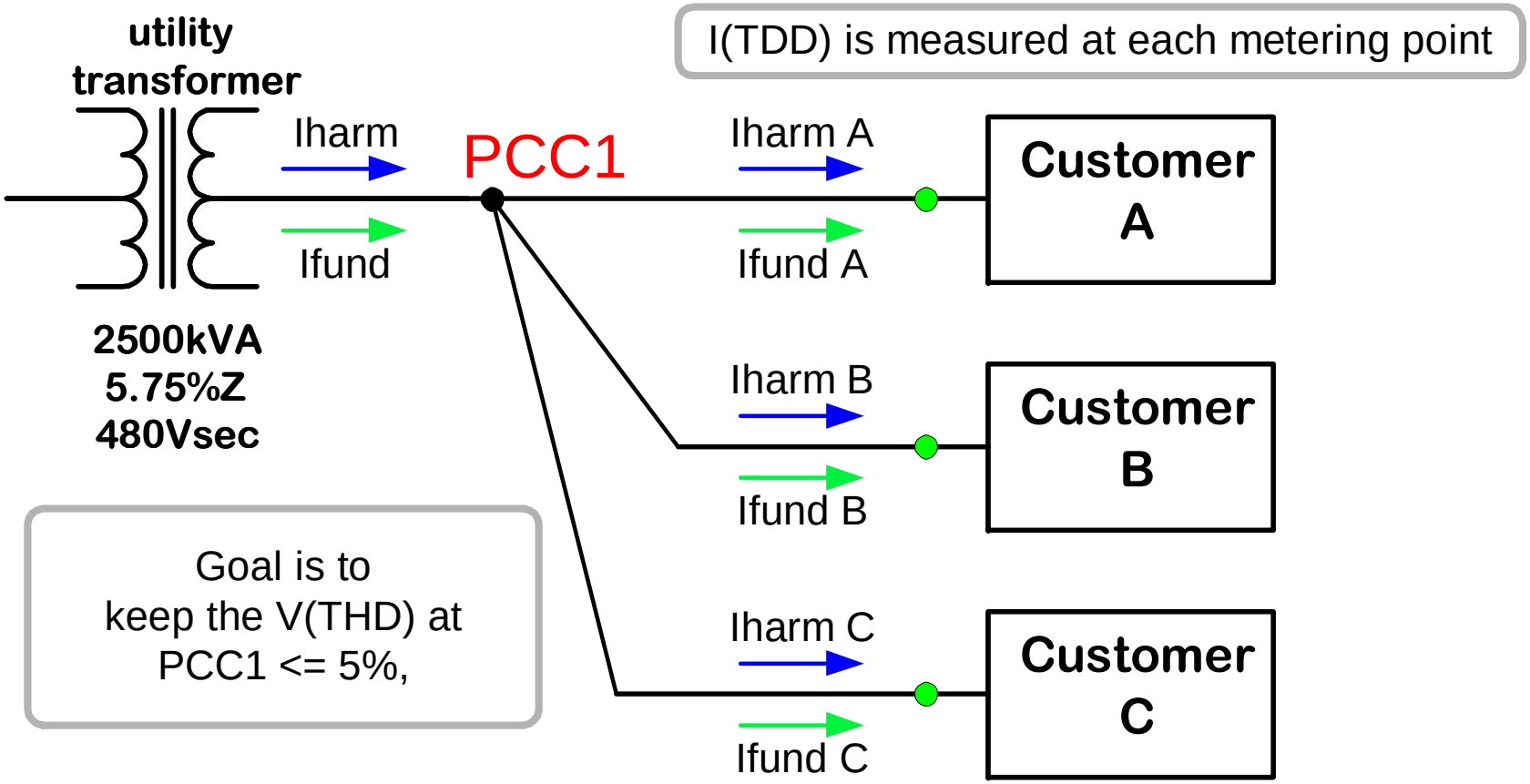
Voltage Distortion depends upon:

- System Impedance's (% Z)
- Amplitude of the Injected Harmonics

PLANT ONE LINE DIAGRAM



Who is your neighbor?



How to Tackle Harmonics?

- It is not economical or desirable to eliminate all harmonics
- Analysis & guidelines are necessary to determine whether or not there are problems created by existing harmonics

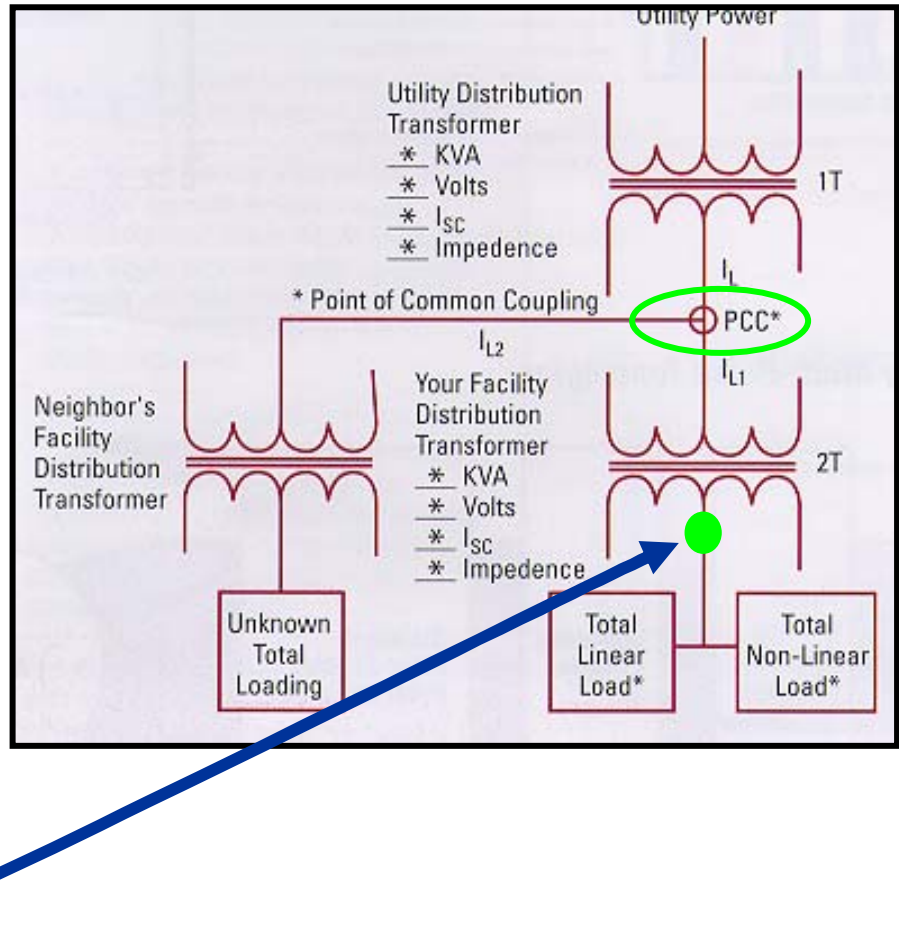
- Useful Guidelines & Standards available are:
  - IEEE- 519 is the Main Standard in North America
    - (places limits on voltage distortion & current THD)
  - IEC- 555 for Europe & some areas of South America
    - (places limits on voltage distortion)
  - IEC- 61000-3-12 proposed draft
    - (places limits on voltage distortion for input current >16A and < 75A)

Harmonic Distortion Limits of IEEE-519

- Developed by utilities,electrical equipment manufacturers and power consumers
- Recommended Harmonic Limits are based on reasonable voltage distortion limits at

  (PCC)
  - PCC is where two or more customers share a common utility power source
- Distortion is Relative to the total plant load
  - i.e. each plant's harmonic limit is different
- Specification Harmonic Limits increasingly common in low voltage systems

PLANT ONE LINE DIAGRAM



Voltage Distortion Limits of IEEE-519

Harmonic Voltage Distortion at PCC in %

	< 6.9 kV	6.9 kV- 13.8 kV	> 13.8 kV
Maximum individual harmonic component	3.0 %	1.5 %	1.0 %
V_{THD}	5.0 %	2.5 %	1.5 %

- IEEE 519 Harmonic Standard for power systems has:
  - ⇒ GENERAL limit set at 5% THD
  - ⇒ HOSPITAL , AIRPORT limit set at 3% THD

Current Distortion Limits of IEEE-519

Maximum Harmonic Current Distortion in % of Fundamental

I_{sc} / I_L	h < 11	11< h < 17	17< h < 23	23< h < 35	THD

- I_{sc} ⇒ system short circuit current at PCC.
- I_L ⇒ maximum load demand at PCC.
- THD ⇒ Total Harmonic Current Distortion allowed at PCC.
- Higher (I_{sc} / I_L) ⇒ measure of power system "stiffness"

Current Distortion Limits of IEEE-519

Maximum Harmonic Current Distortion in % of Fundamental

I_{sc} / I_L	h < 11	11< h < 17	17< h < 23	23< h < 35	THD
< 20	4.0	2.0	1.5	0.6	5.0
20 - 50	7.0	3.5	2.5	1.0	8.0
50 - 100	10.0	4.5	4.0	1.5	12.0

- Higher (I_{sc} / I_L) ⇒ "stiff" power system ⇒ more THD allowed
- Designing a system with a strong power source diminishes the impact of harmonics. If a back-up generator is utilized, this should also be taken into consideration.

Current Distortion Limits of IEEE-519

Maximum Harmonic Current Distortion in % of Fundamental

I_{sc} / I_L	h < 11	11< h < 17	17< h < 23	23< h < 35	THD
< 20	4.0	2.0	1.5	0.6	5.0
20 - 50	7.0	3.5	2.5	1.0	8.0
50 - 100	10.0	4.5	4.0	1.5	12.0

- Worst Case Application of IEEE - 519 $\Rightarrow$ (Isc / IL) < 20 Category

What are the IEEE 519-1992 standards?

Harmonic Voltage Limits	Table 10.2
Low-Voltage Systems	
Application	Maximum THD (%)
Special Applications - hospitals and airports	3.0%
General System	5.0%
Dedicated System - exclusively converter load	10.0%

Current distortion Limits for General Distribution Systems (120V through 69,000V)						
Maximum Harmonic Current Distortion in Percent of Iload						
Isc/Iload	<11	11<=h<17	17<=h<23	23<=h<35	35<=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
Even harmonics are limited to 25% of the odd harmonic limits above						
						Table 10.3
Isc=maximum short circuit current at PCC						
Iload=maximum demand load current (fundamental frequency component) at PCC						

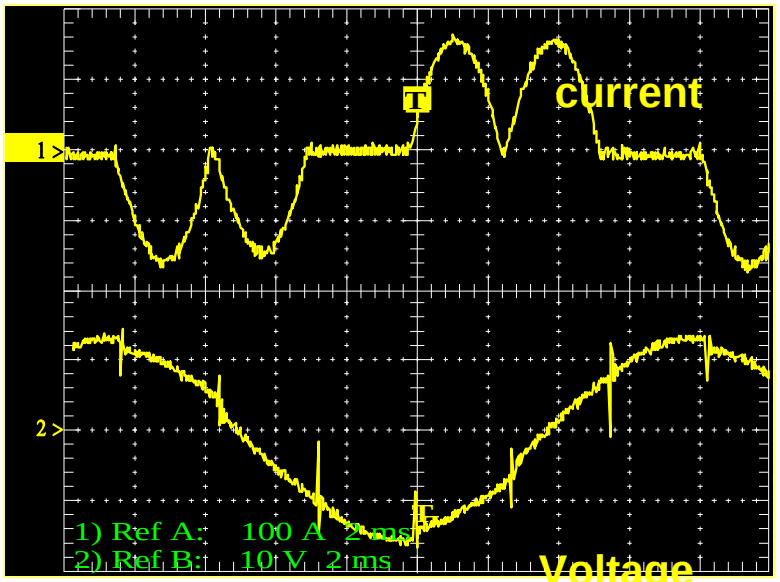
Harmonic Mitigation Techniques

When Non-Linear Loads exceed 30% - 50% of Total Load, an harmonic analysis of the plant one-line load diagram should be performed.

How can we reduce the harmonic current?

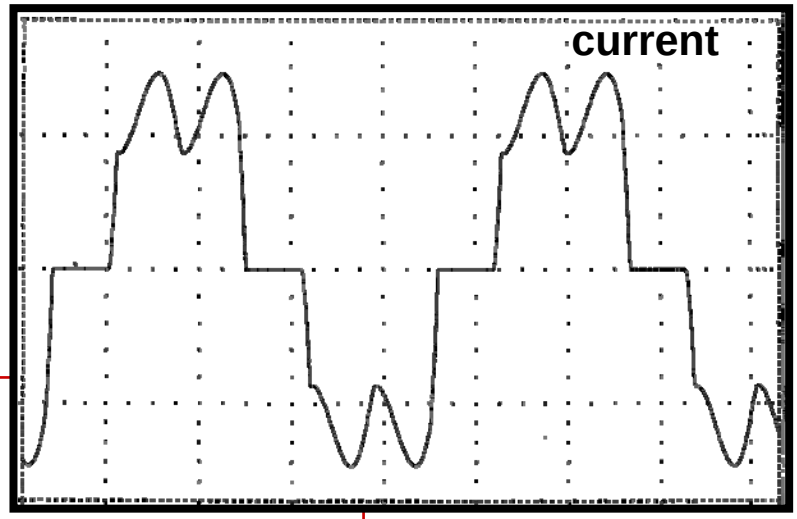
- DC link choke within the drive
- line reactor
- passive filter
- active filter
- multi-pulse converters
- active front-end

Input Current of 6-Pulse Rectifier



Standard Configuration - "no" DC link Choke

- Current THD= 80% @ full load
- THD depends on source impedance(%Z)
- Rectifier diode turn off causes voltage spikes on voltage waveform
- For Single drives < 5 HP, low impact on utility

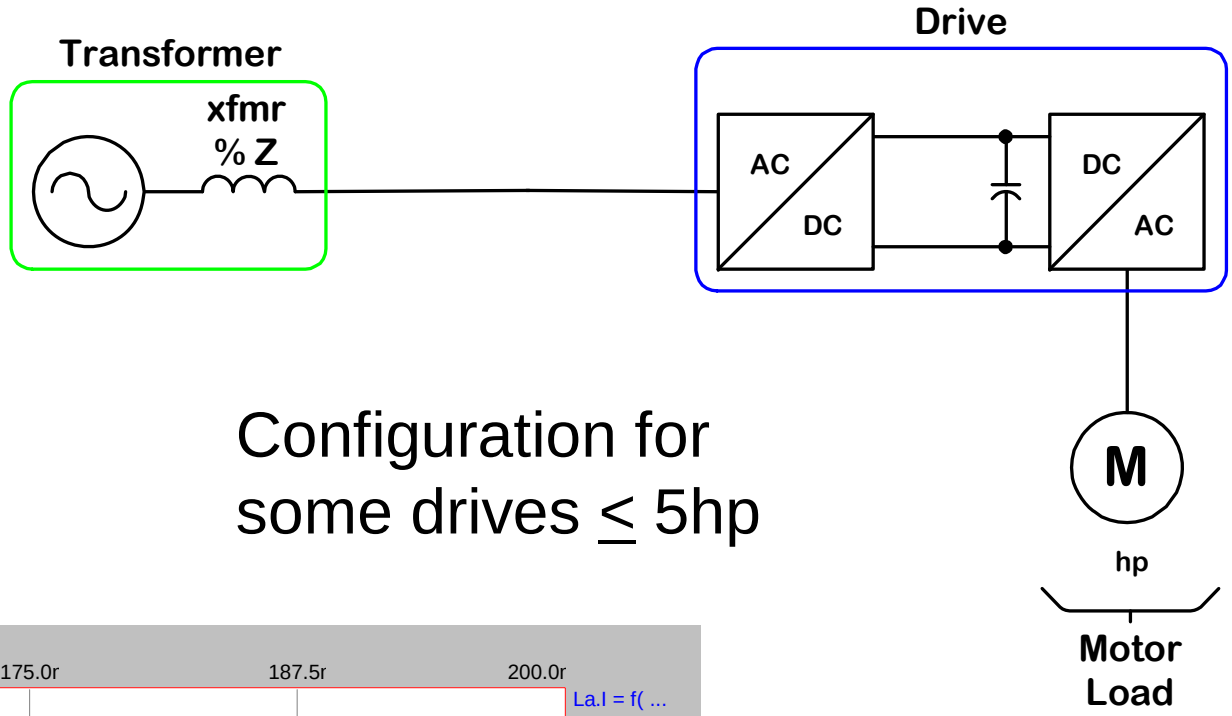


Standard Configuration - "with" DC link Choke

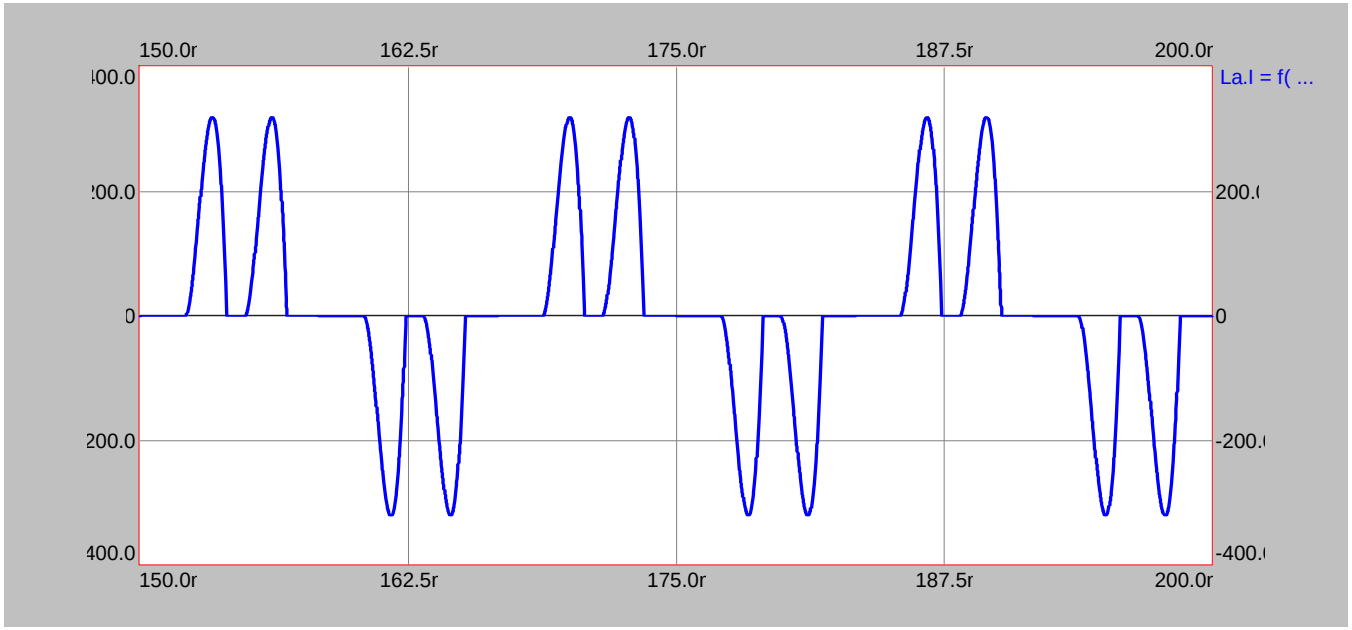
- Current THD= 32% @ full load
- THD independent of source %Z
- Good power factor = 0.93
- Minimizes input voltage distortion

Drive w/o DC Link Choke

- Typical I(THD) of 80 to 120%
- Sensitive to line voltage transients
- High peak line currents



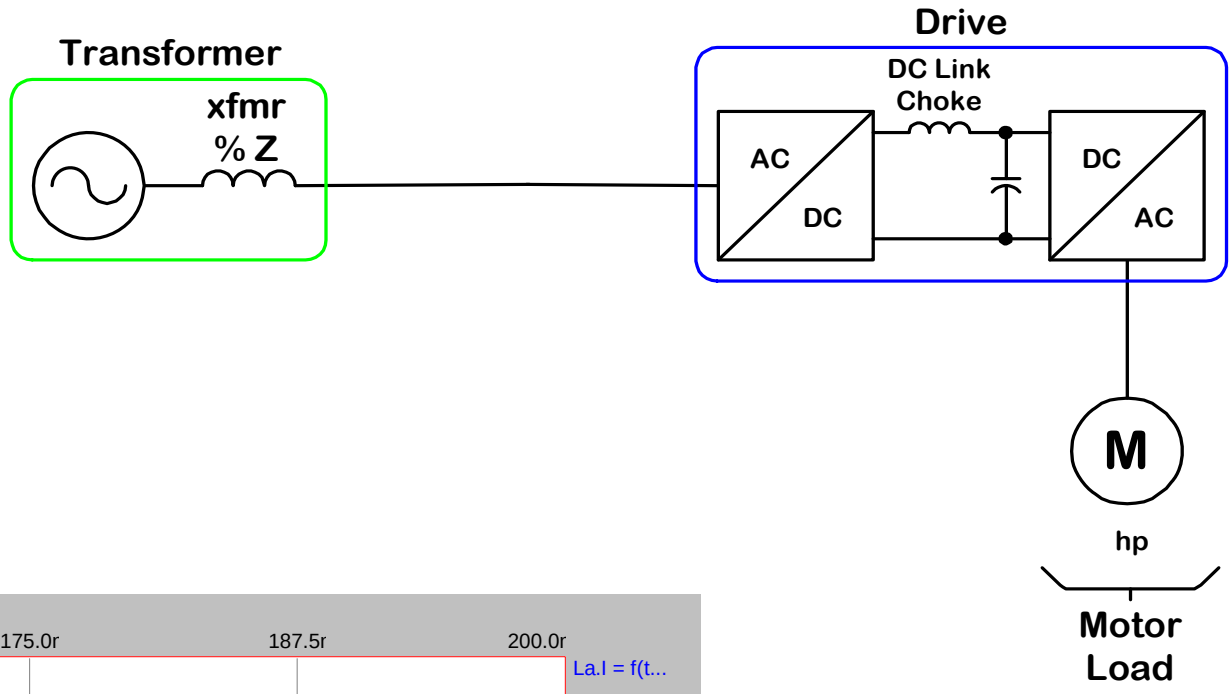
Configuration for some drives ≤ 5hp

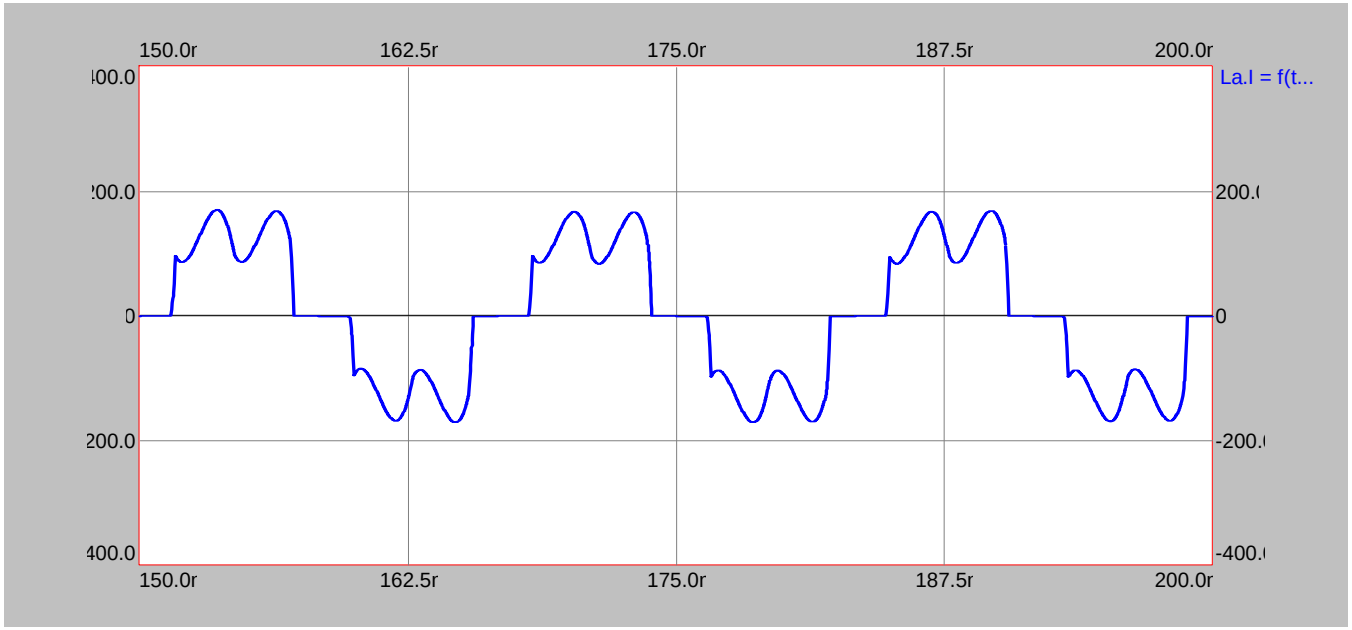


NOTE: Ipk about 3x Irms

Drive with DC Link Choke

- Typical I(THD) of 30 to 40%
- Less sensitive to line transients

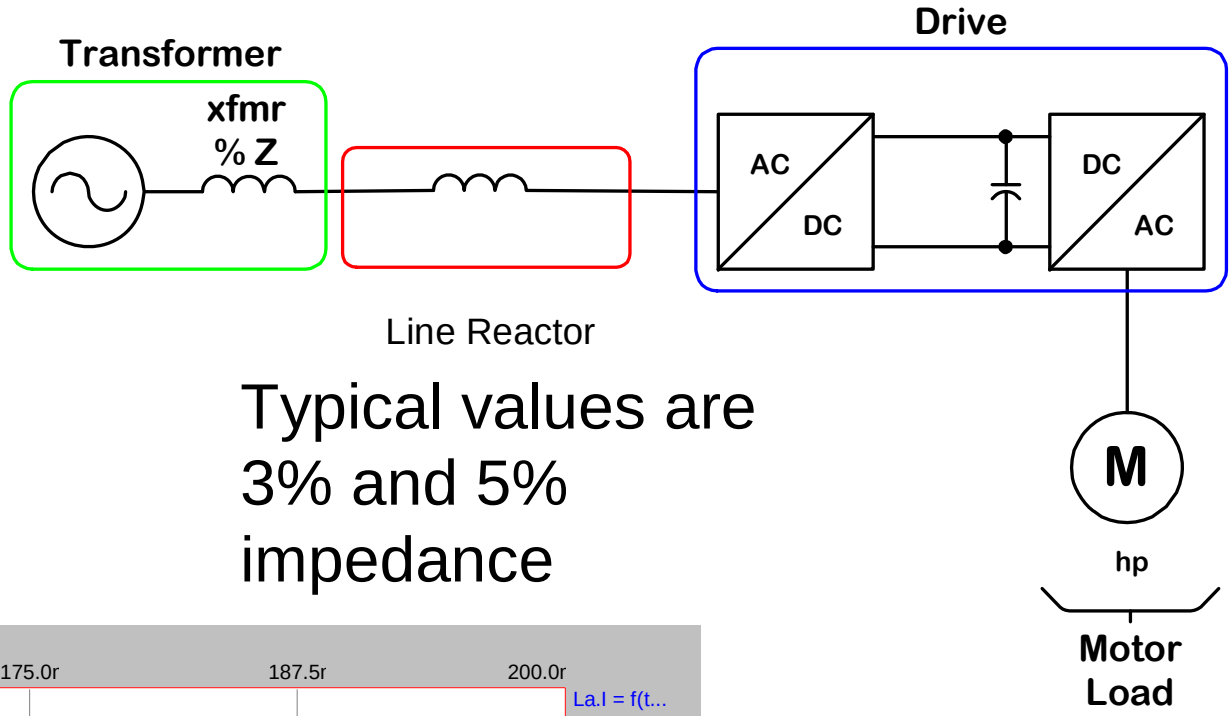




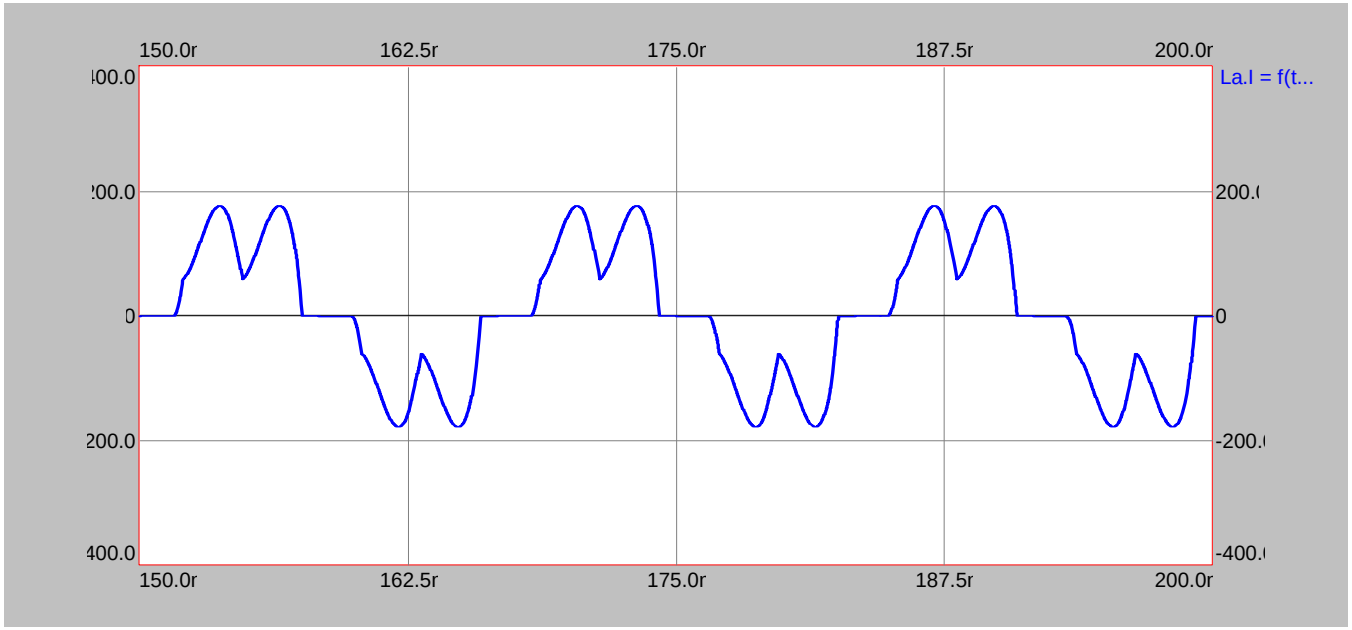
NOTE: Ipk about 1.5x Irms

Line Reactor, Drive w/o DC Link Choke

- Typical I(THD) of 30 to 45%
- Big help for drives without DC link choke



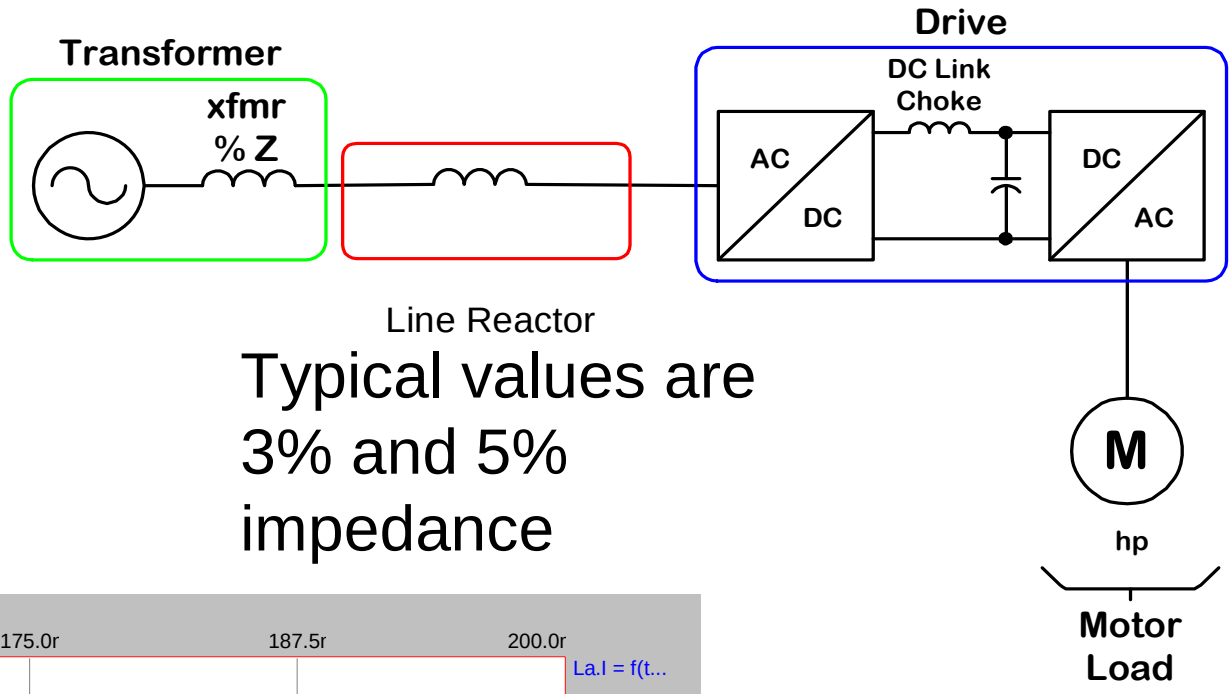
Typical values are 3% and 5% impedance



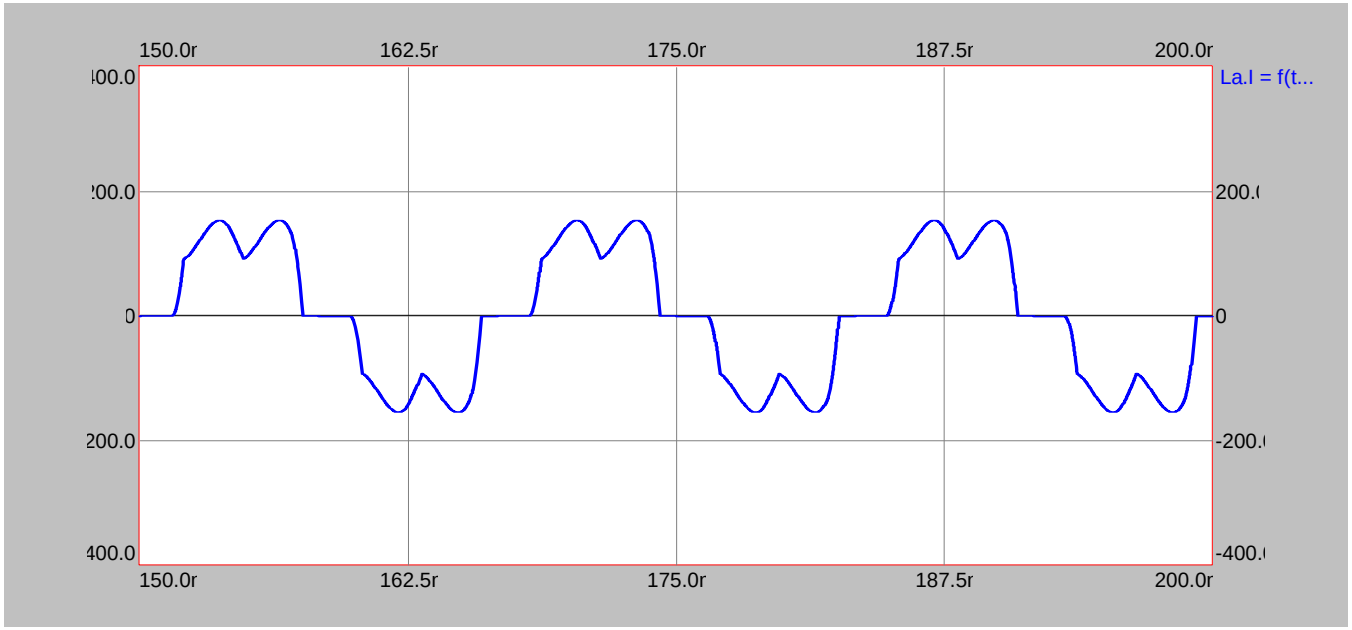
NOTE: shown is 3% LR

Line Reactor

- Typical I(THD) of 20 to 35%
- Big help for drives without DC link choke



Typical values are 3% and 5% impedance



NOTE: shown is 3% LR

Harmonic Mitigation Technique - Passive & Active Filters

Passive Filters:

eliminate/reduce specific harmonics (tuned 5th, 7th filters)
reduce higher order harmonics (low pass, 5th thru 17th)

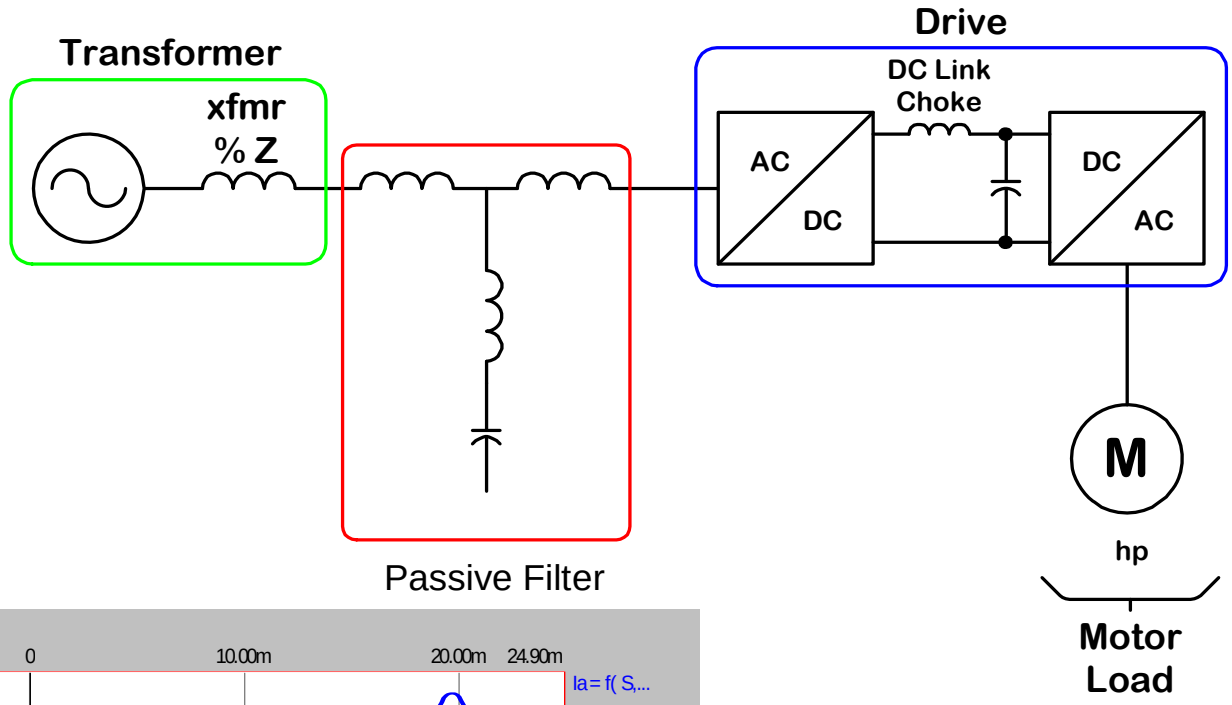
Active Filters:

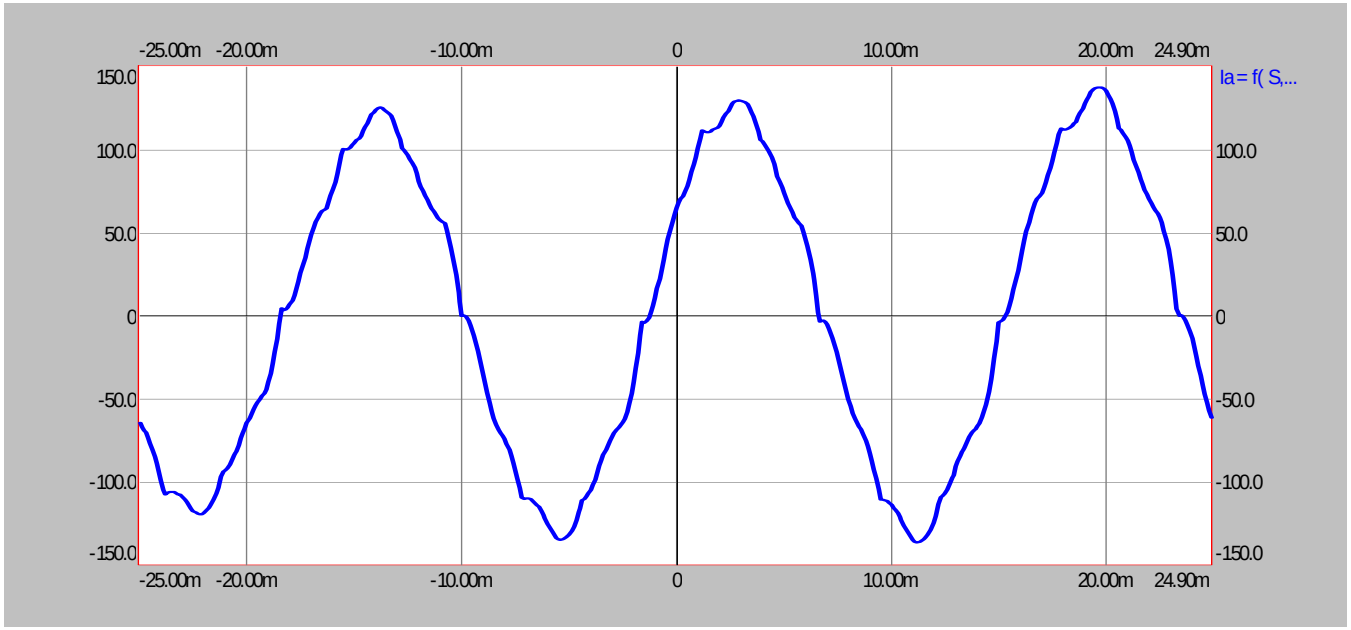
using switching converters to compensate for specific harmonics and/or improve Power Factor
It injects equal and opposite of Drive harmonics into AC line

Let's, look at these solutions in more detail !

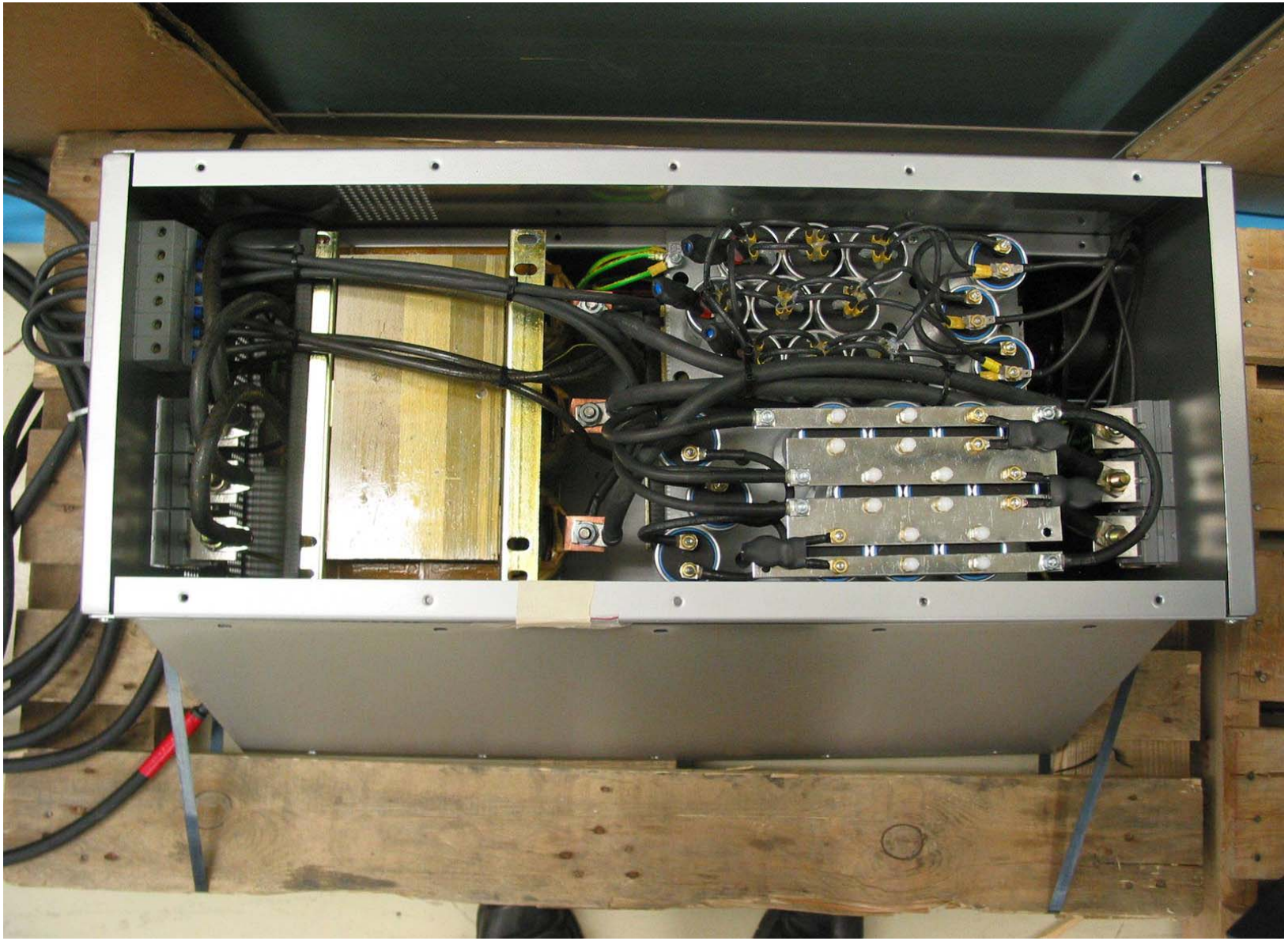
Passive Harmonic Filter

- Typical I(THD) of 5 to 8%



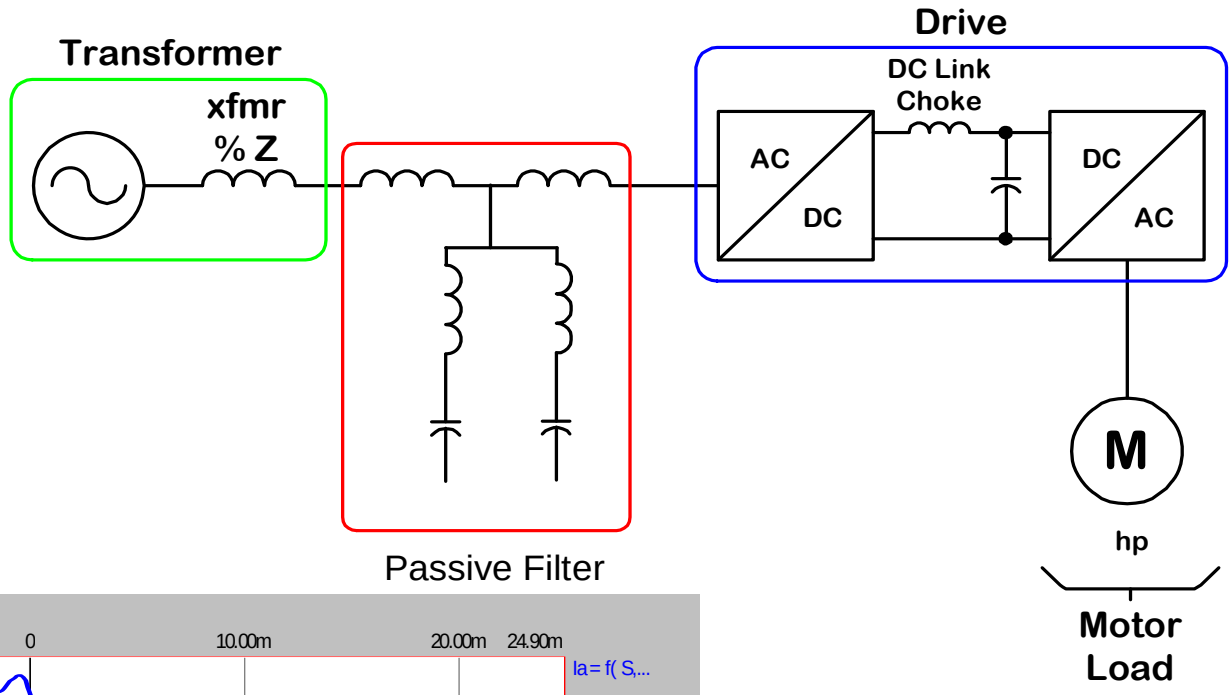


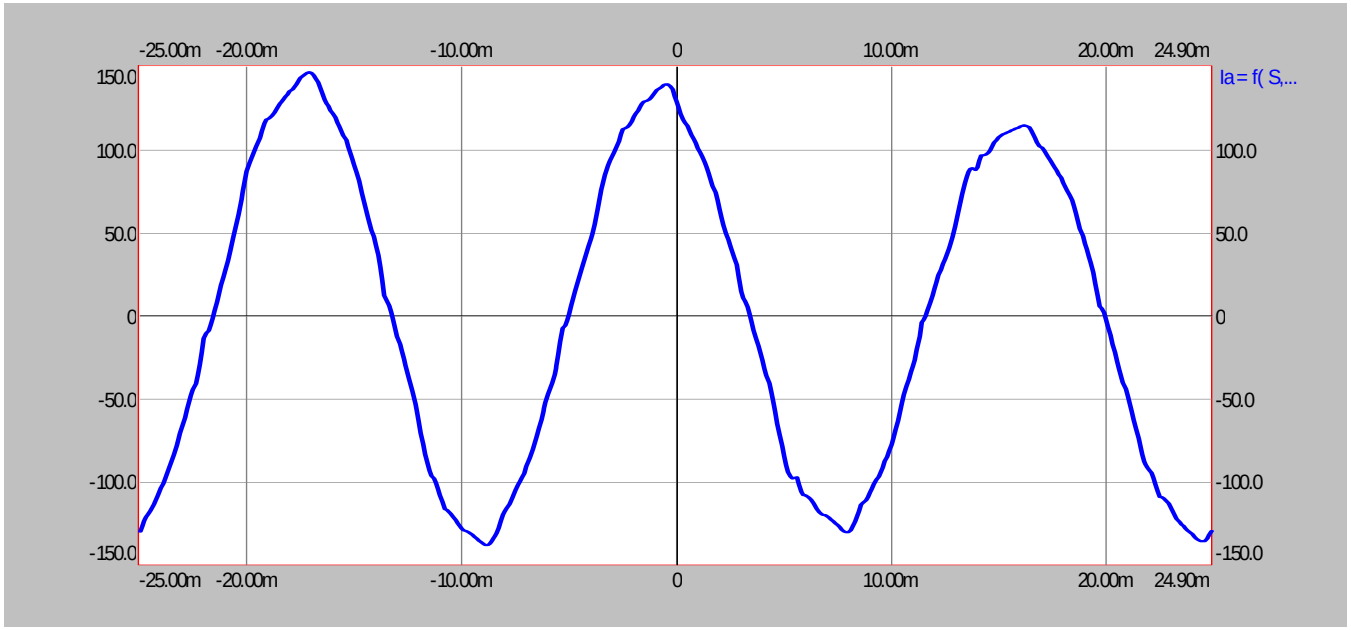
Passive Harmonic Filter



Passive Harmonic Filter - Dual

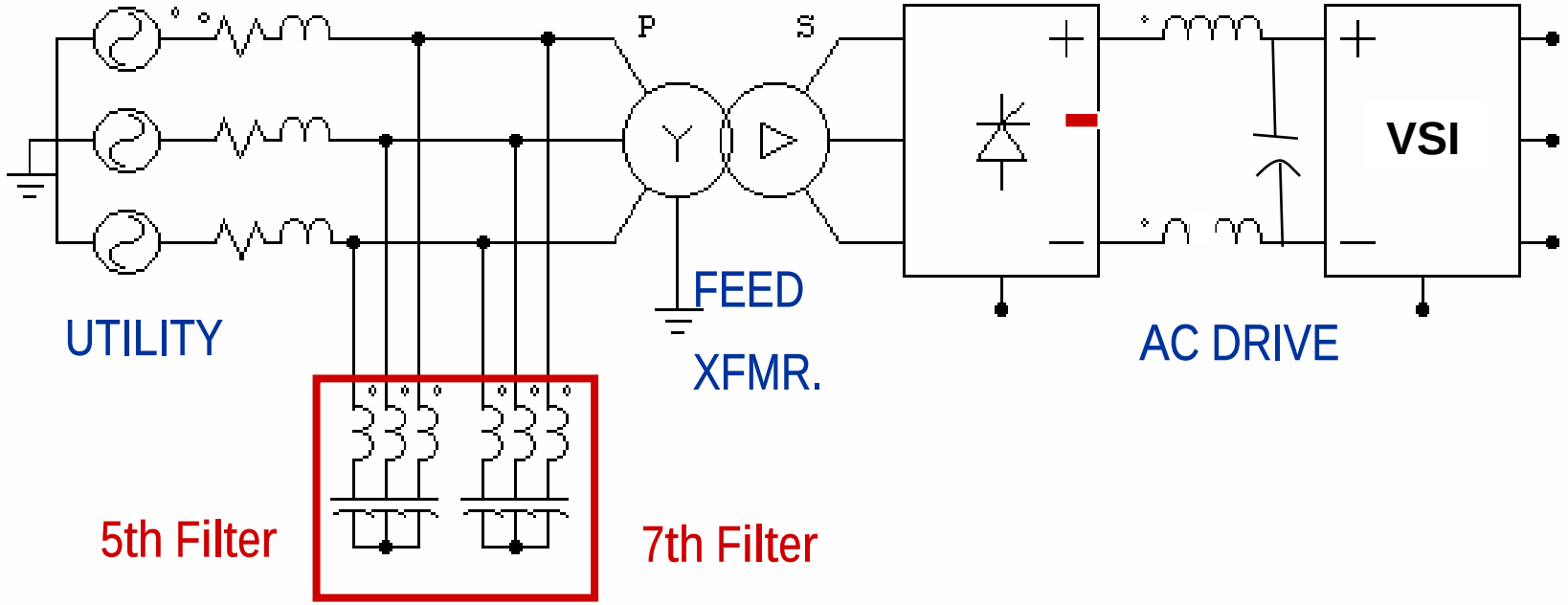
- Typical I(THD) of 4 to 7%





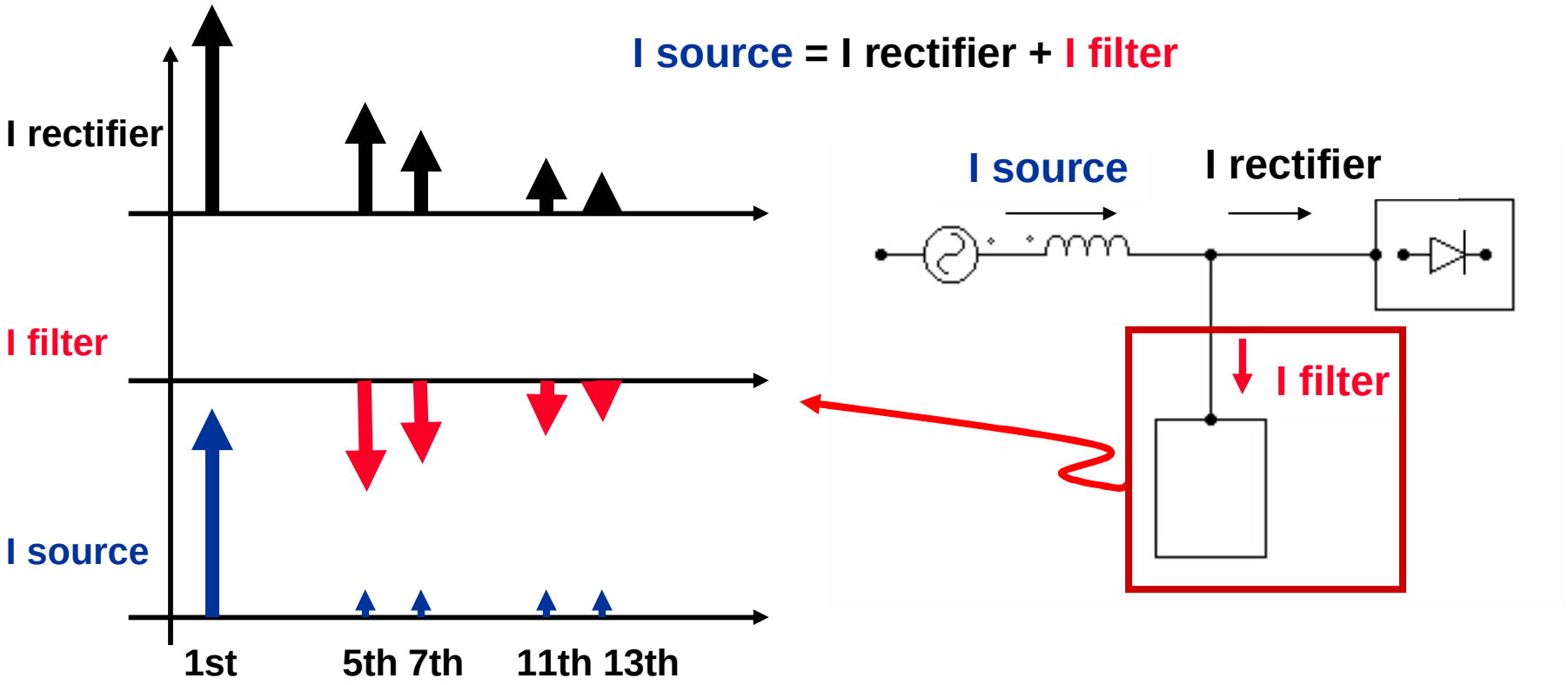
Passive Filter: Harmonic Trap Filter

6-pulse rectifier with tuned 5th & 7th filter



Consists of one or more tuned 5th or 7th LC filters in shunt with power system.
Usually connected at the primary of the isolation transformer or line reactor.
Filters interact with other plant non-linear loads, can sink for unknown load.
Need overload and fuse blown detection (usually individually fused).

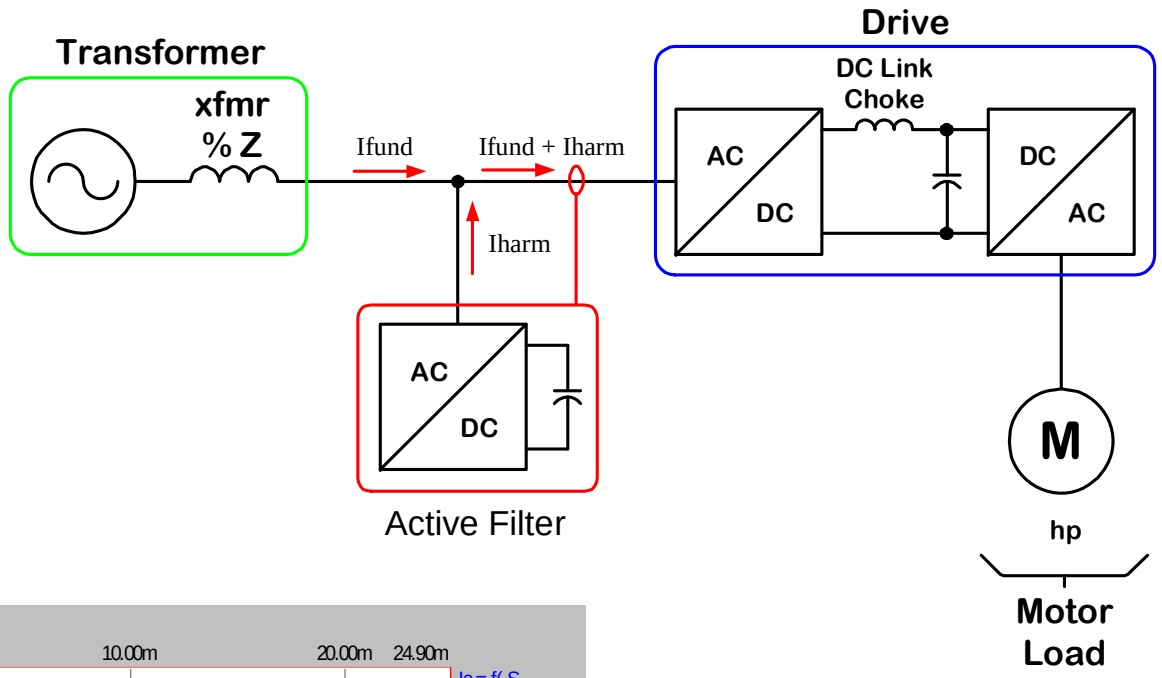
Active Filter Concept



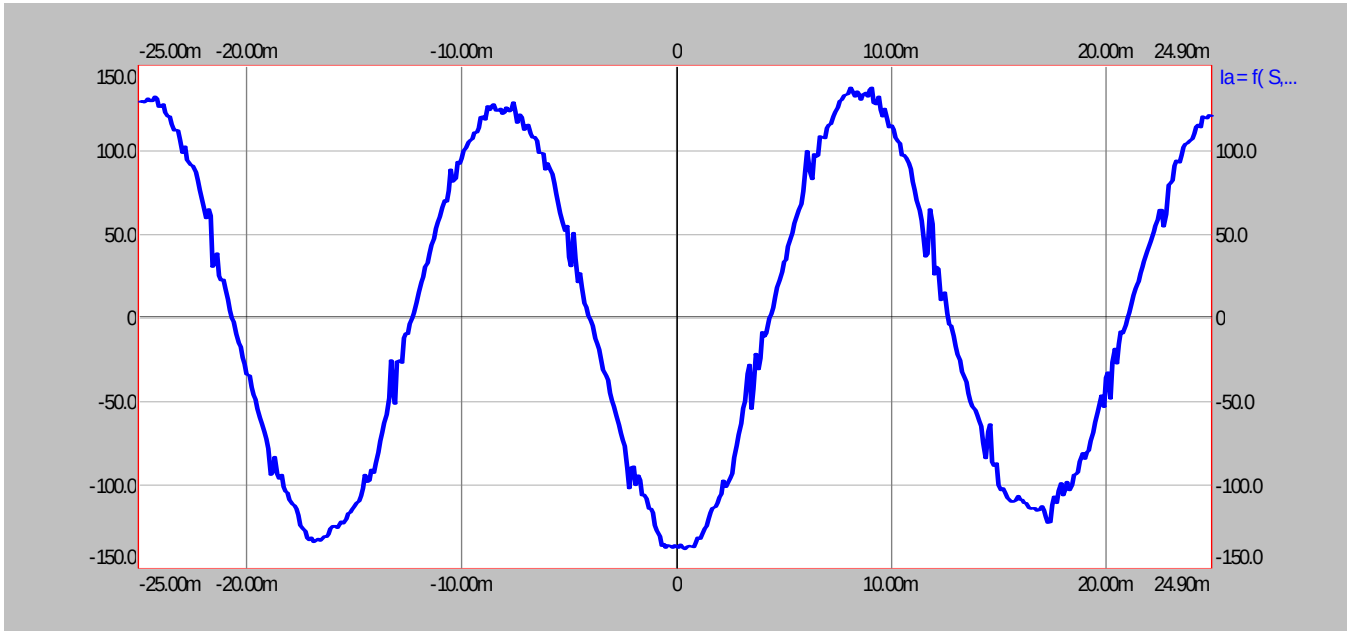
- High Filter Converter ratings: ~ 1/3 of Drive kVA
- Multi-functional: reactive power factor compensation, voltage and load balancing

Active Harmonic Filter

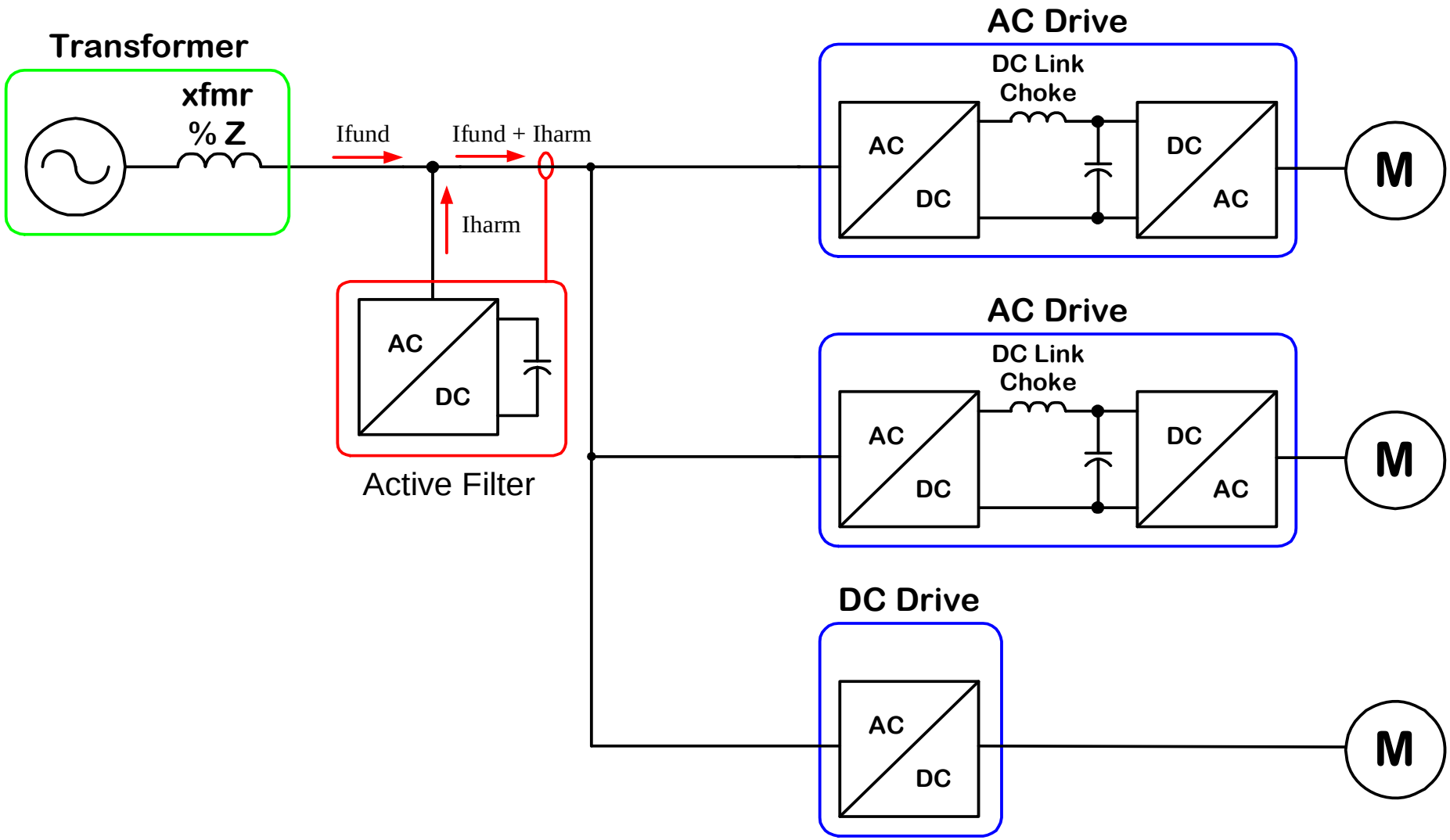
- Typical I(THD) of 3 to 6%



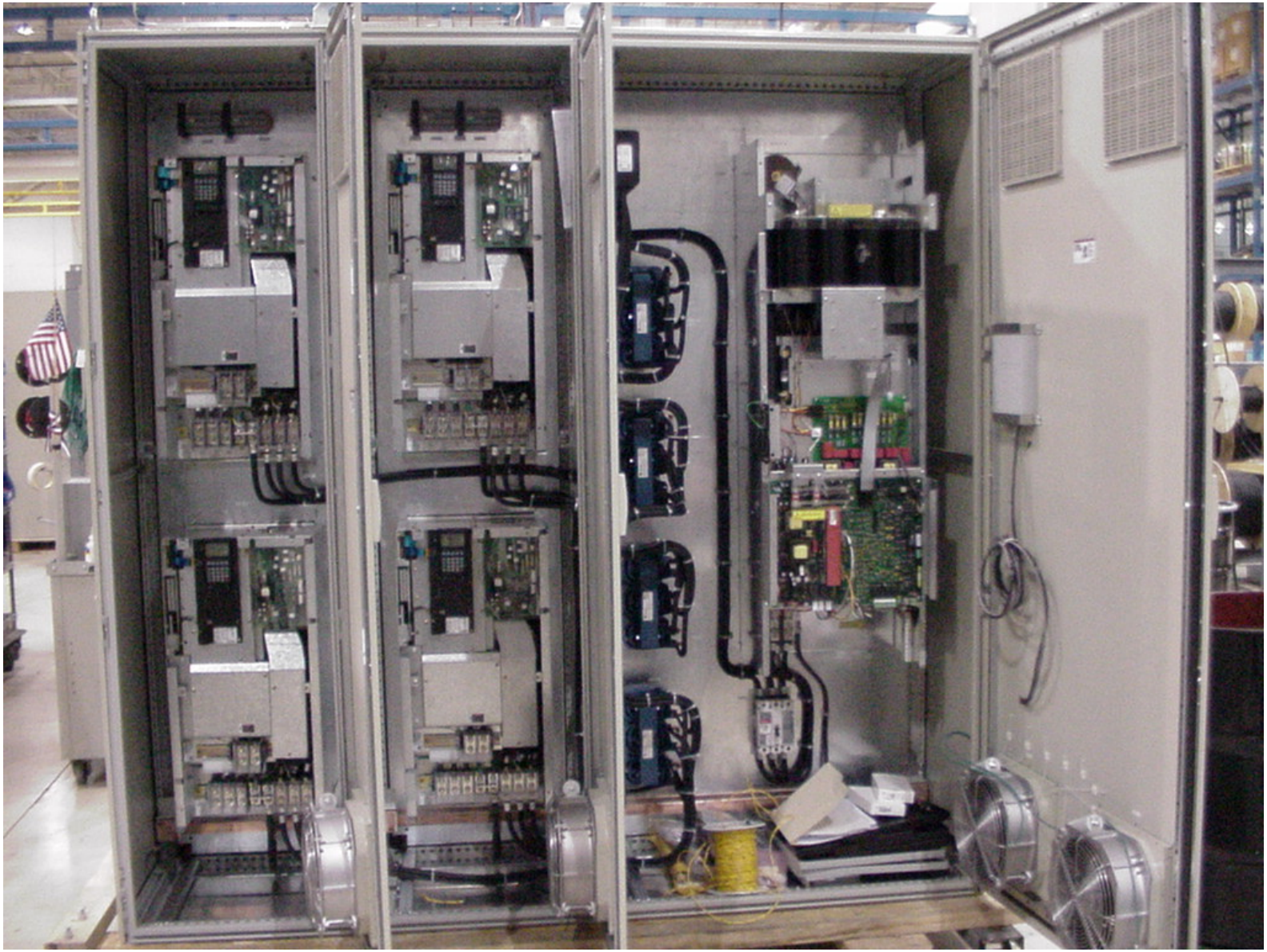
Current from Transformer



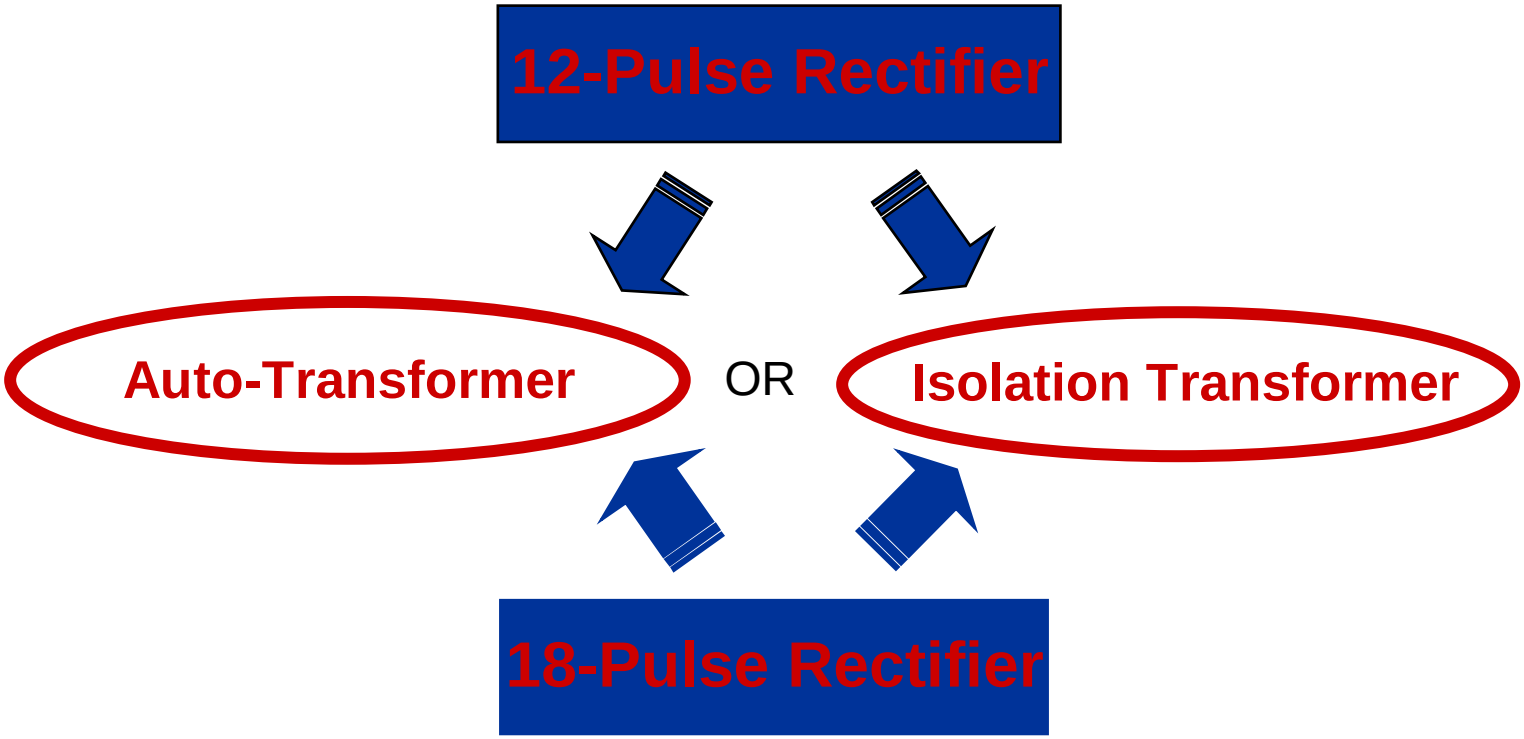
Active Harmonic Filter



Active Harmonic Filter



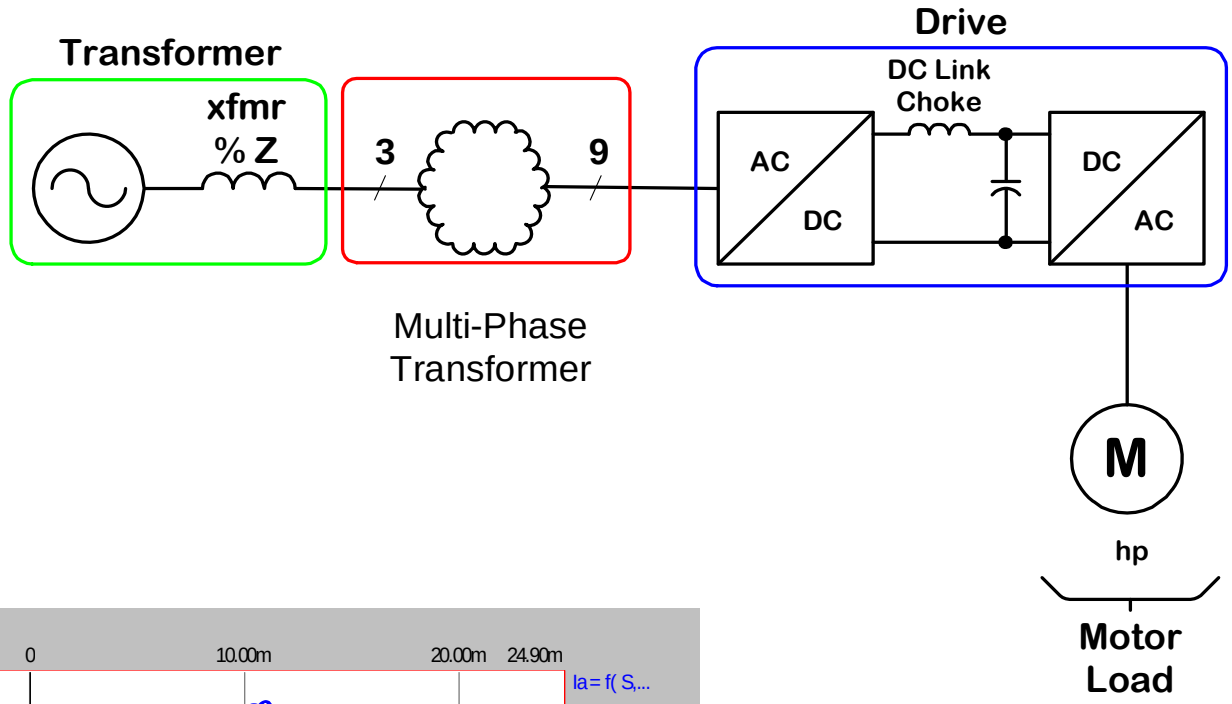
Harmonic Mitigation Technique
Rectifier's with Higher Pulse Number

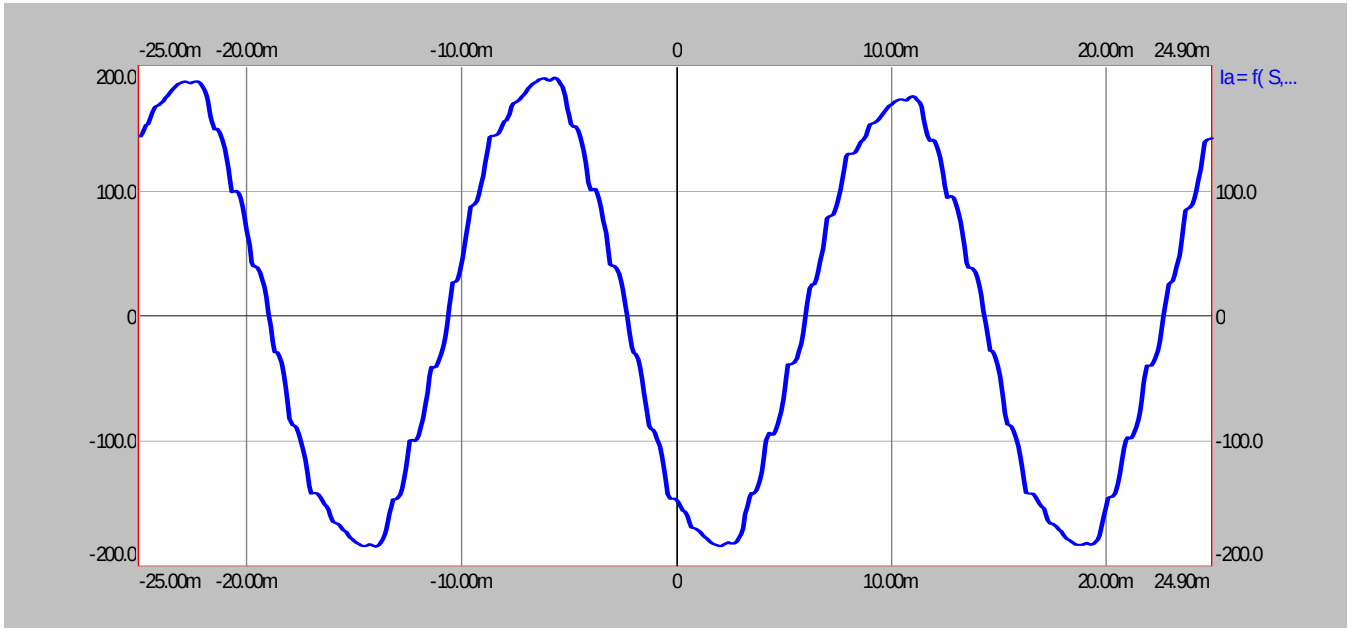


- 18-pulse drives produce less THD, but are larger & more expensive
- Isolation transformers produce less THD, but larger & more expensive

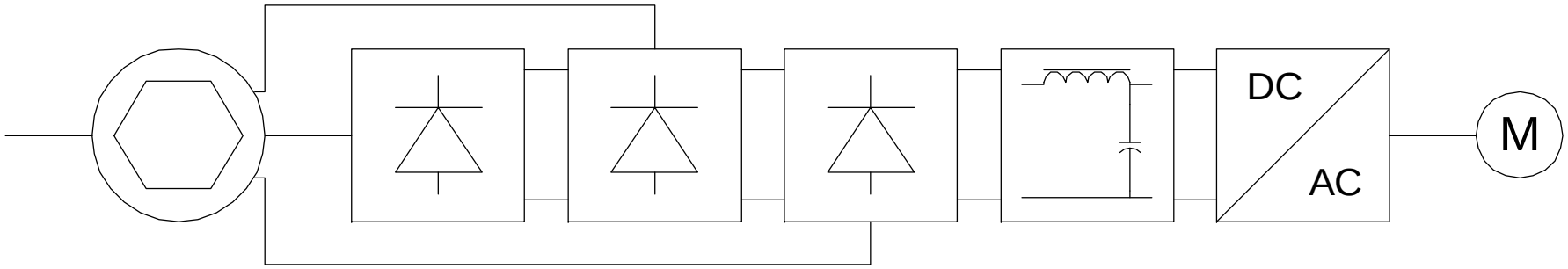
Multi-Pulse Converters

- 12-Pulse Typical I(THD) of 9 to 12%
- 18-Pulse Typical I(THD) of 4 to 5%





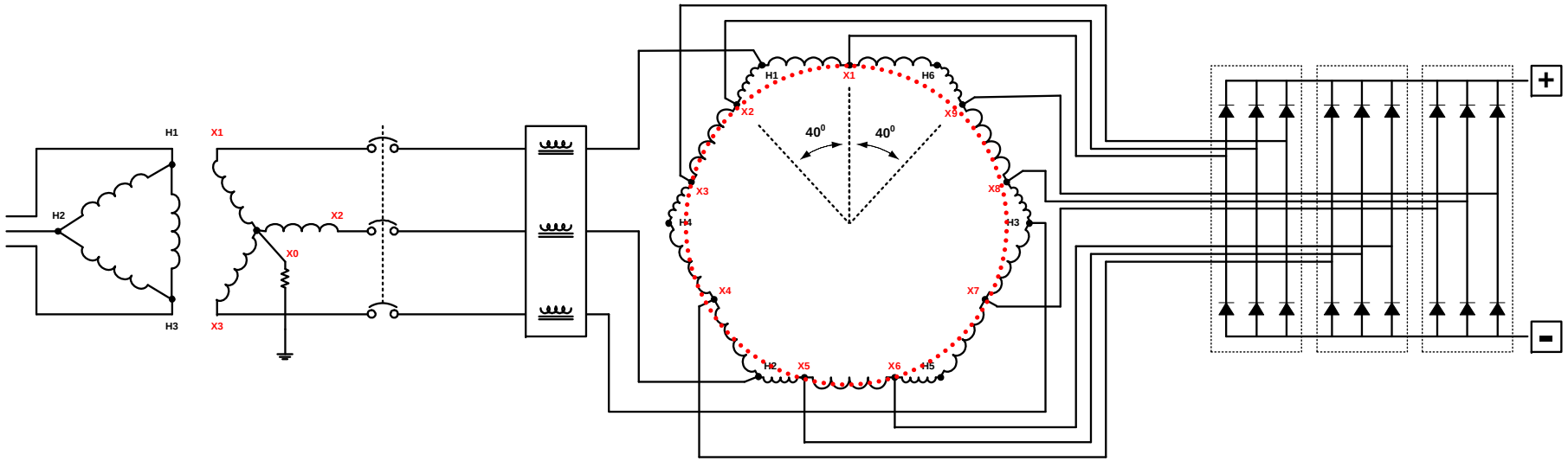
18-Pulse, Parallel



- Auto-transformer with polygon windings (480V primary for 480V drive)
  - 1/3 the size of the isolation xfmr
  - Can have isolated primary - larger
- Diode bridges are in parallel – one third current rating
- 9 wires from transformer to bridges
- I(THD) = 3 to 5%

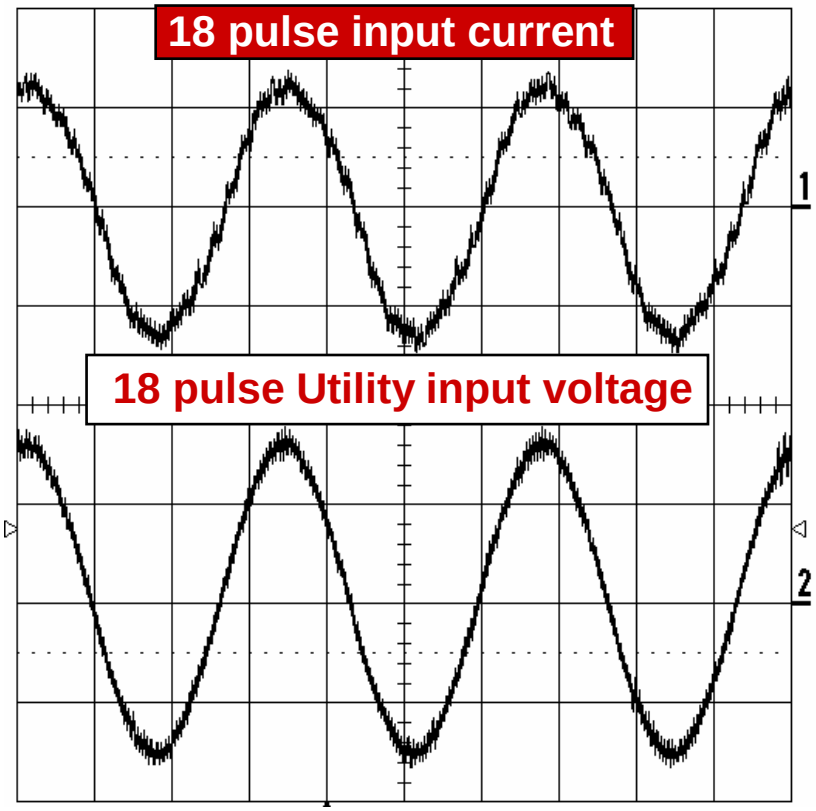
18-Pulse Auto-Transformer Converter

Supply Transformer Line Reactor Auto-Transformer 18 Diode Bridge



NOTE: 5 windings per core leg

Input Waveforms of 18-Pulse Option



FEATURES

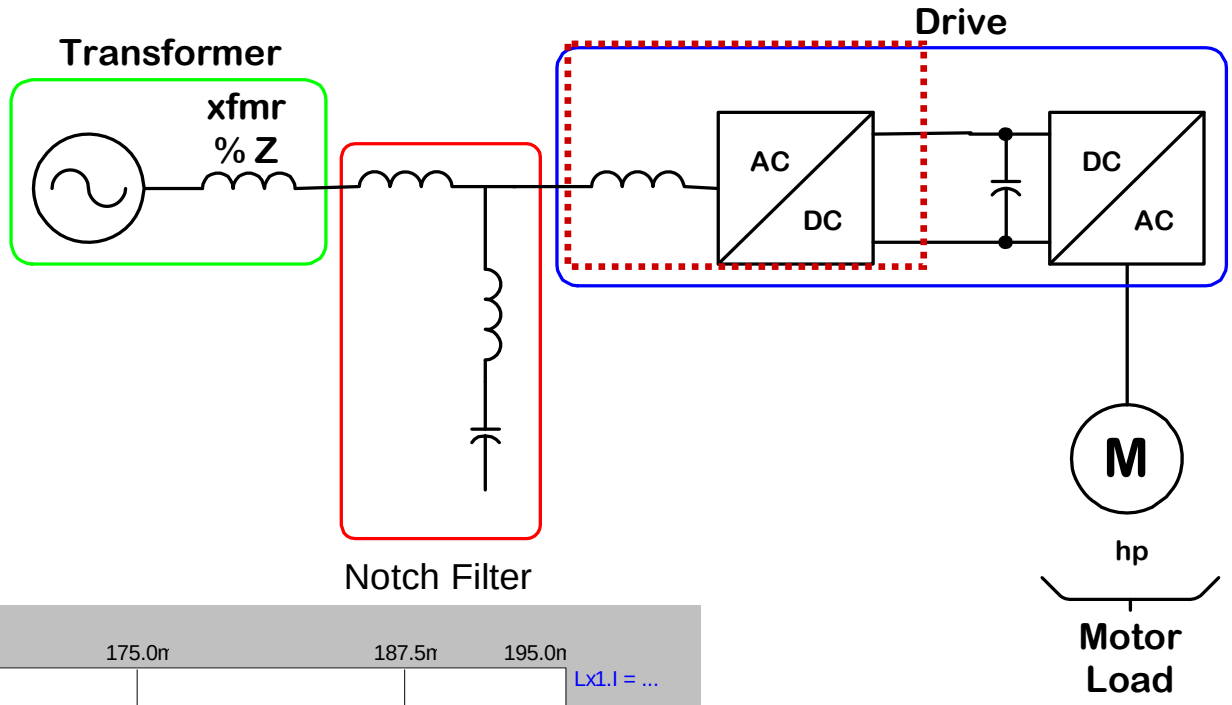
- Meets IEEE-519 5% Harmonic Standard at the drive input Terminal
- Current THD 3.5% full load (typ.), 6 % no load
- 5th, 7th, 11th & 13th harmonic reduced
- Input power factor improved to 0.99, thus reducing kVA source requirements
- Input Diode rectifiers & magnetics lead to a reliable drive system
- More robust and trouble free than Harmonic Trap filters
- Specified for use on high “Z” Aux-Gen unit
- Lower $ than Active PWM Rectifier approach

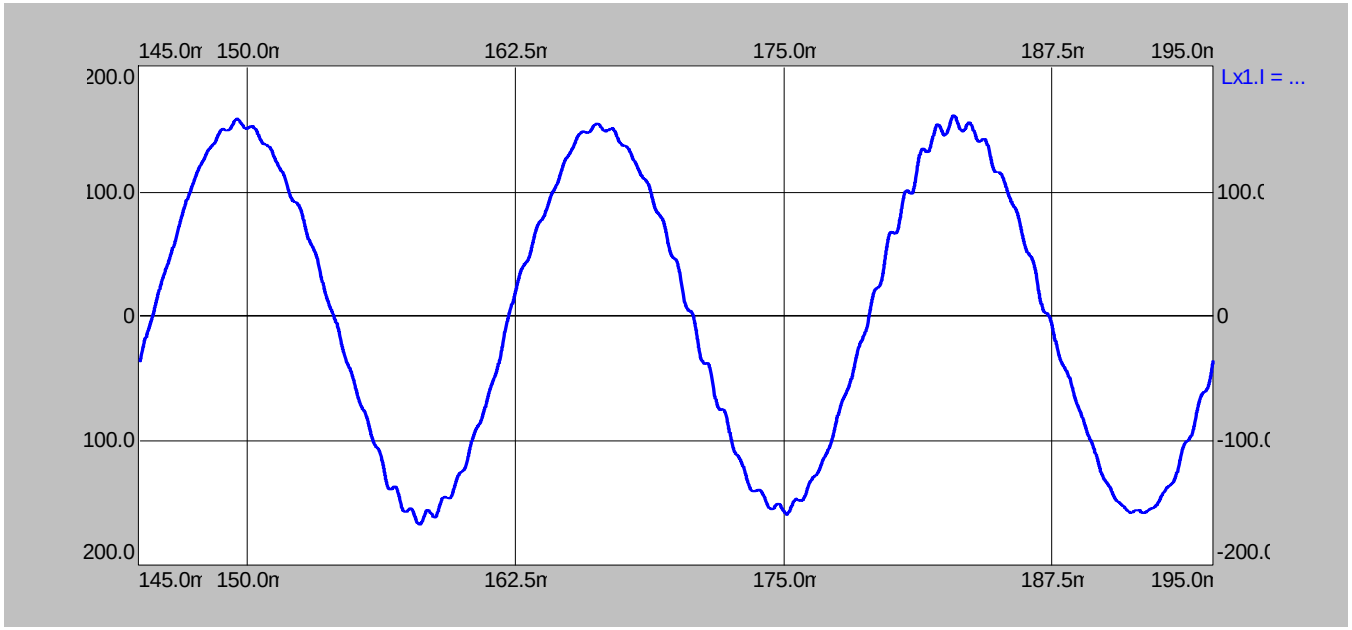
18-Pulse Front-End

- 18 pulse
  - Diode bridge converter
  - Common DC bus drive
  - Auto-transformer

Active Front-End

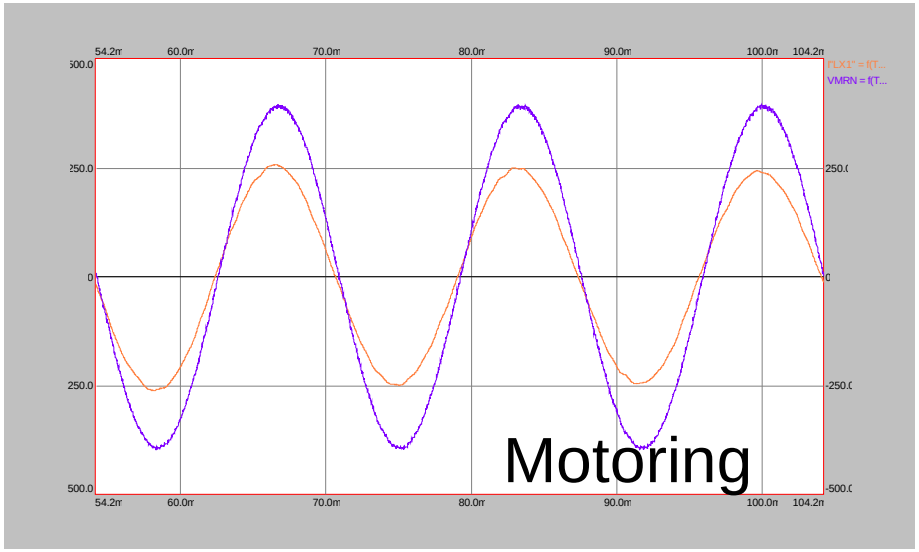
- Typical I(THD) of 3 to 5%

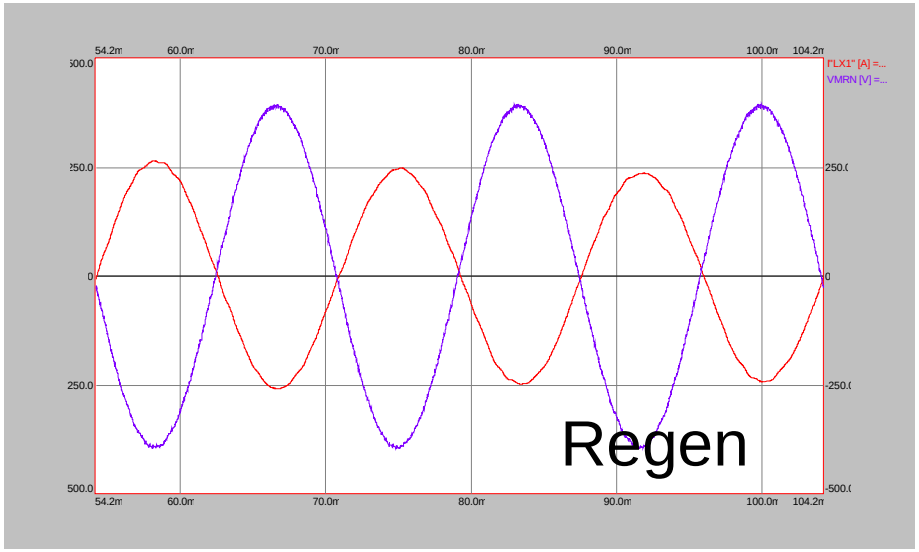




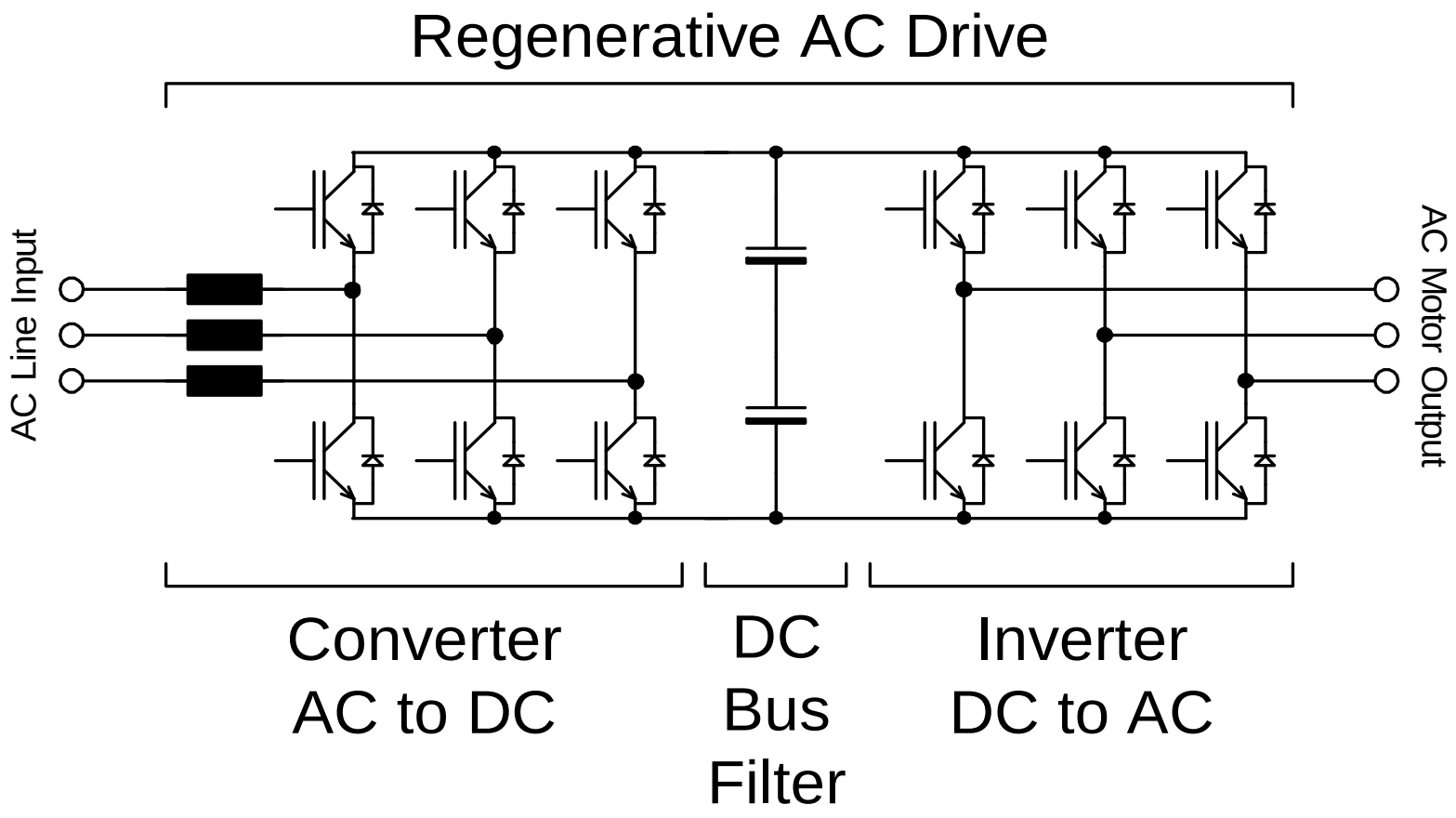
Active Front-End

- Serves as Input to Drive(s)
  - Multiple drives on one DC bus
- Regulated DC Bus
  - Ride Through Capability
  - No loss of motor voltage
- Unity Displacement Power Factor
- Low Harmonics
  - IEEE-519
- Regenerative
  - Energy Saving
  - 100% Regenerative Capacity





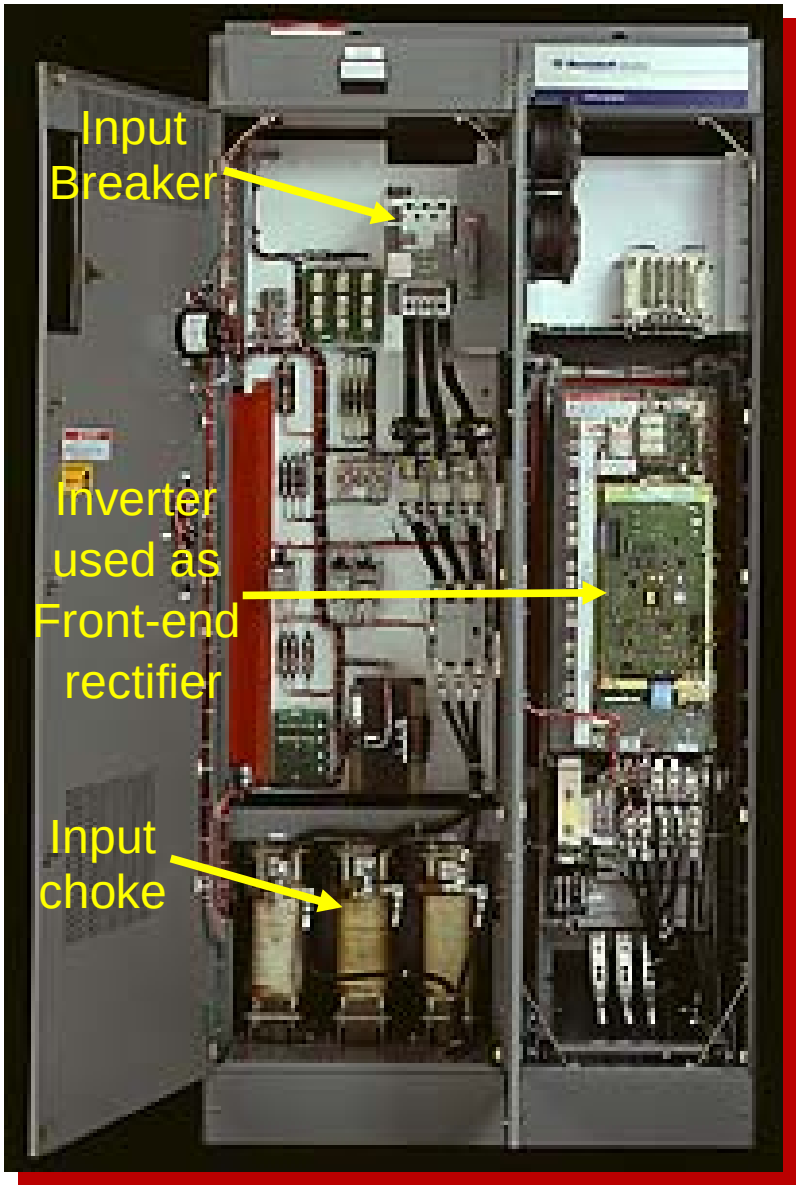
Regenerative AC Drive



Harmonic Mitigation Technique
Active Front End Rectifier

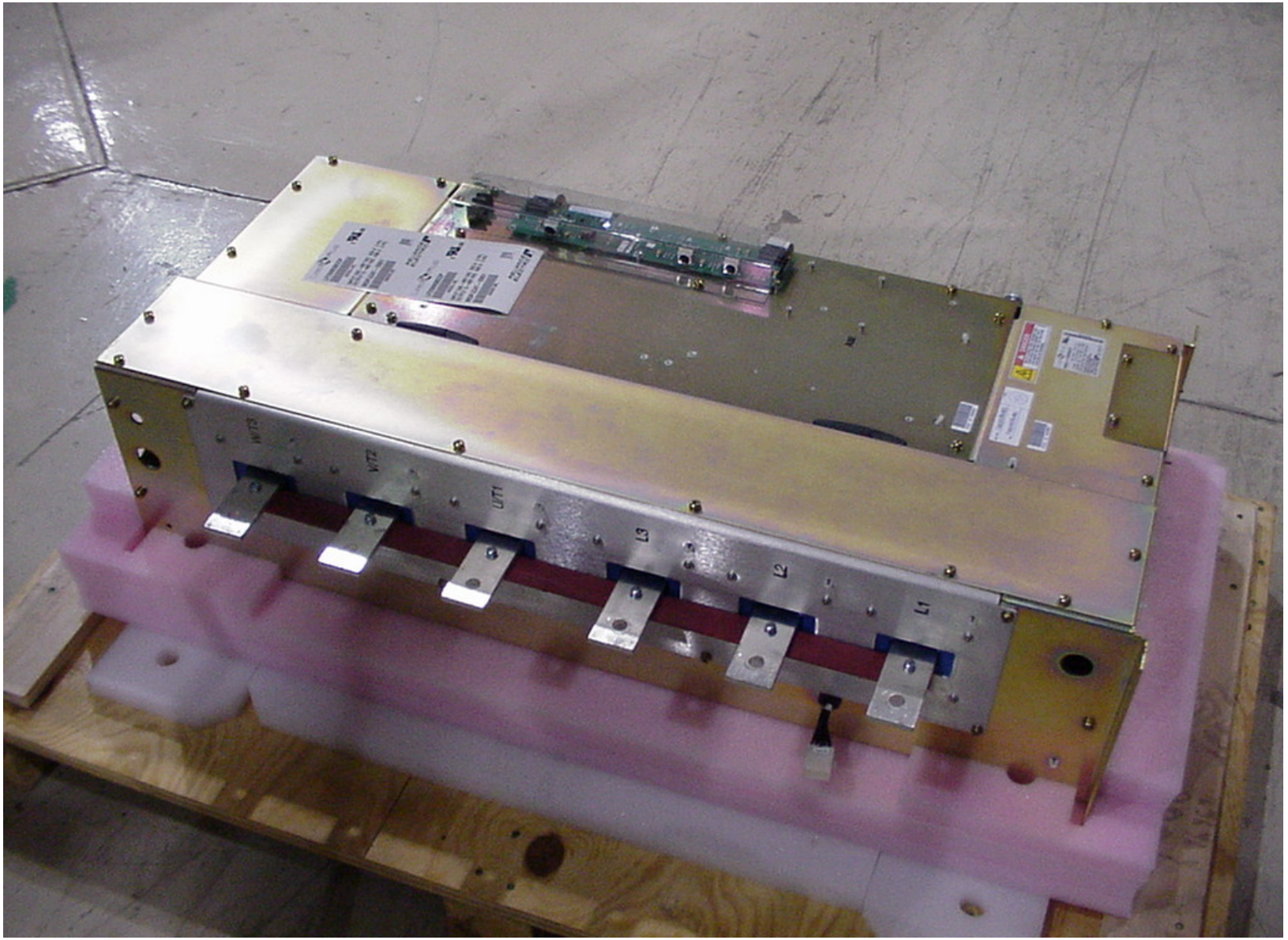
A dual-direction converter that ...

- Supplies forward power to a common DC bus drive system with Sinusoidal input currents
- Regenerates excess power back to the 3-phase AC line with Sinusoidal input currents

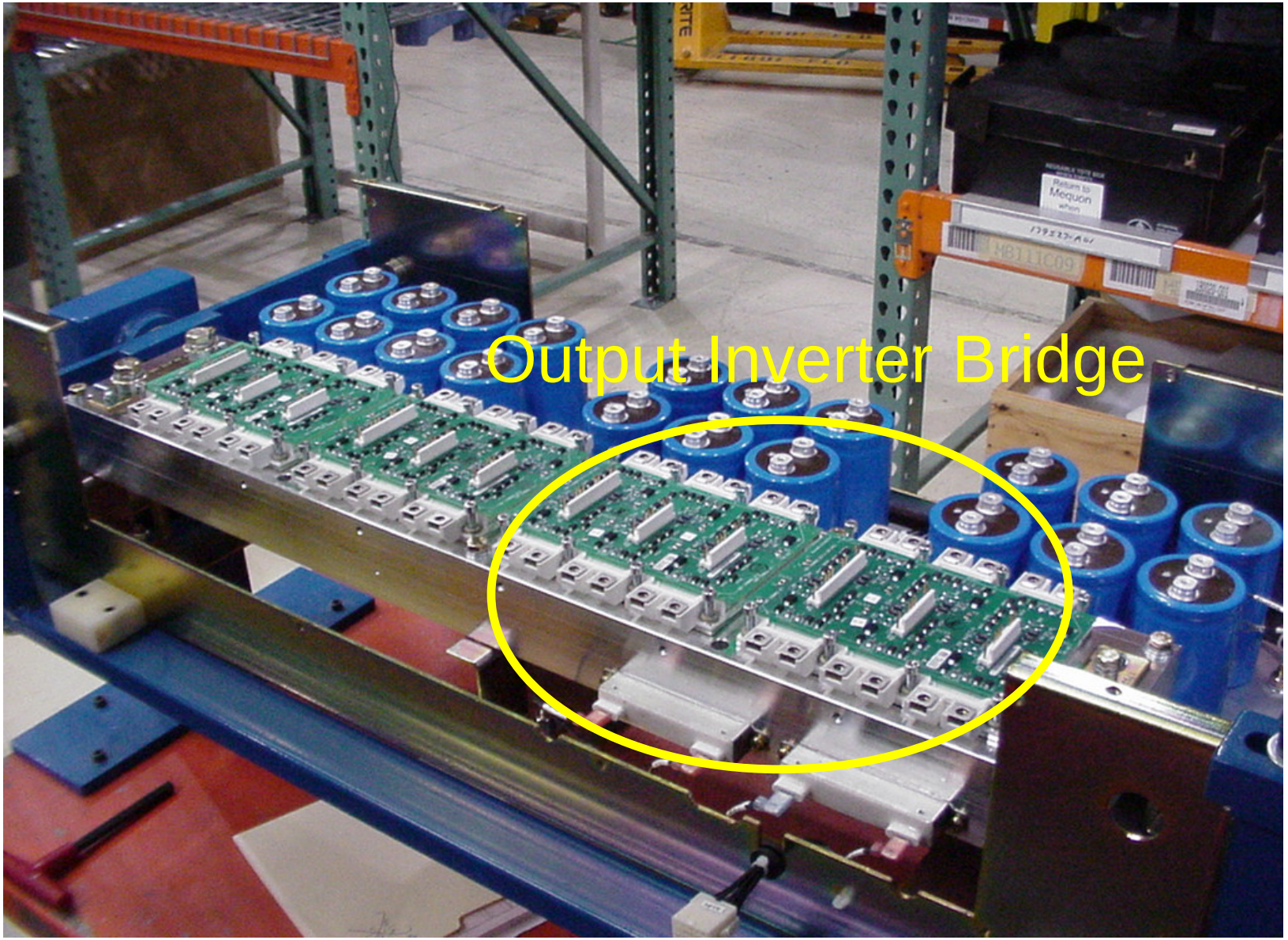


Output: 200A DC
Input: 460V AC, 145 kVA
(K-Code)

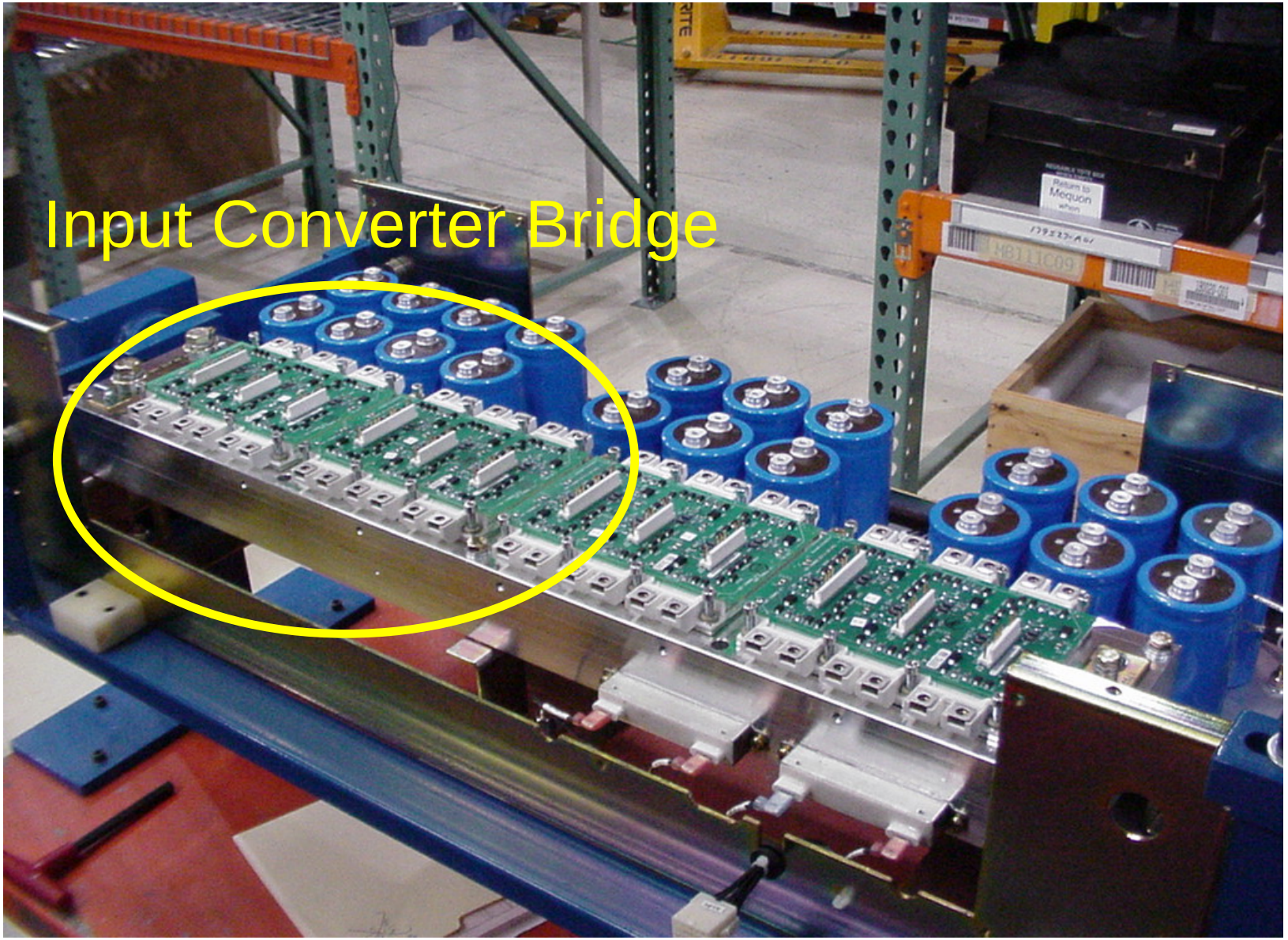
Liquid Cooled Drive

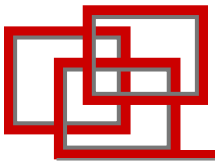


Inverter IGBTs



AFE Converter IGBTs



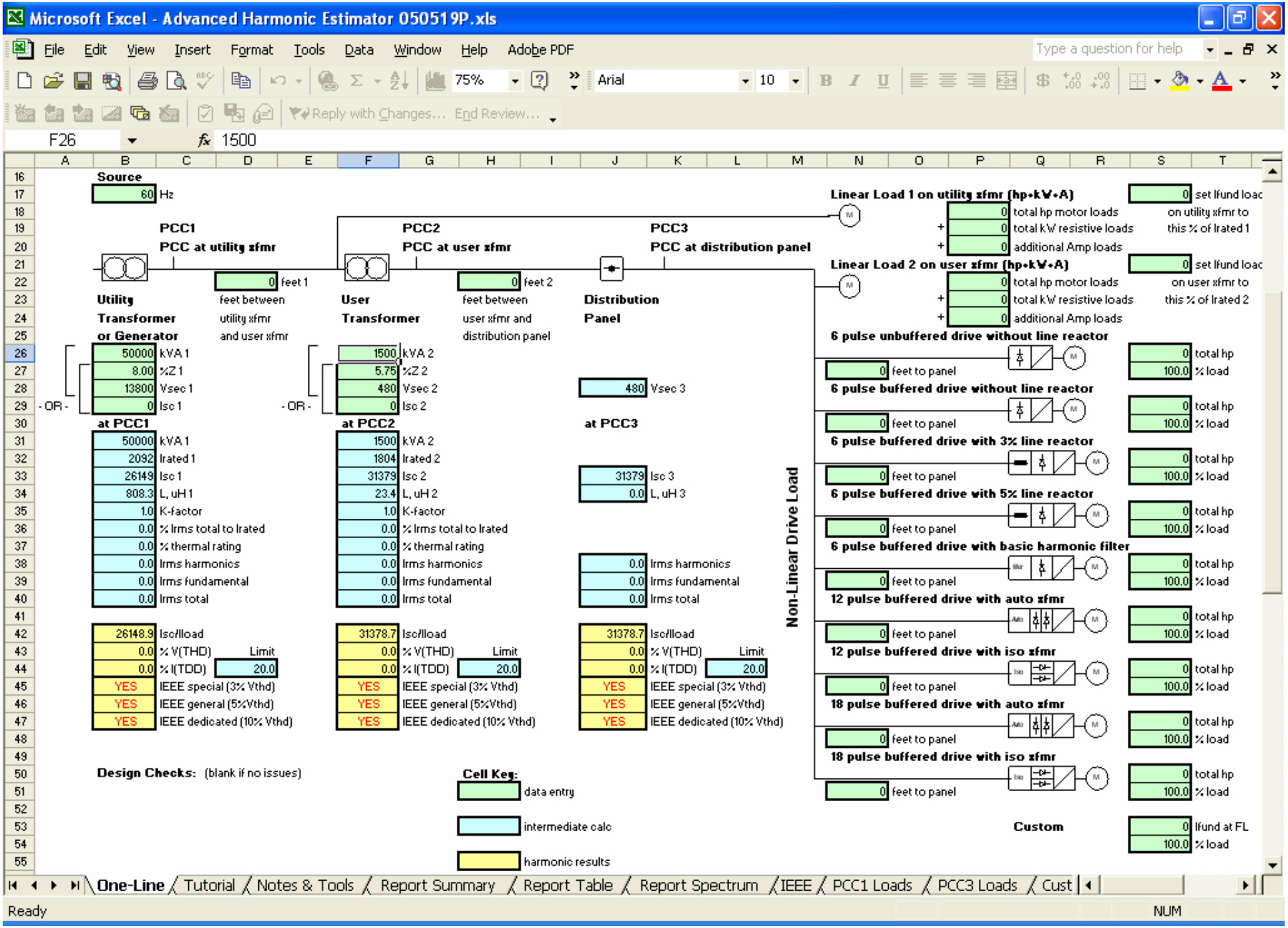


Can we estimate what the harmonics will be?

Rockwell Automation Can Help Choose the Right Solution

"I don't know where to start!"

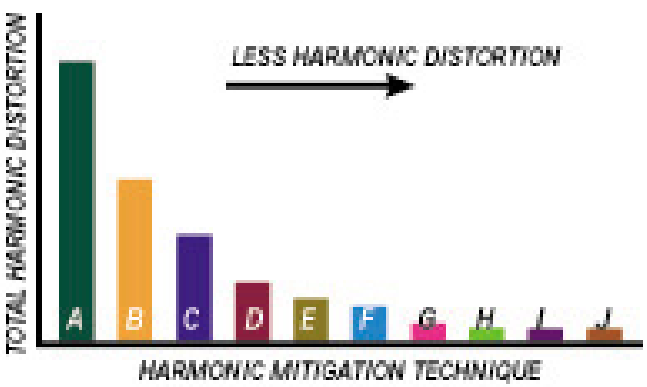
- What is needed?
  - Power distribution drawing showing utility and feed transformer specifications
  - Maximum Short Circuit Current (this figure comes from the utility)
  - Linear and non-linear loads

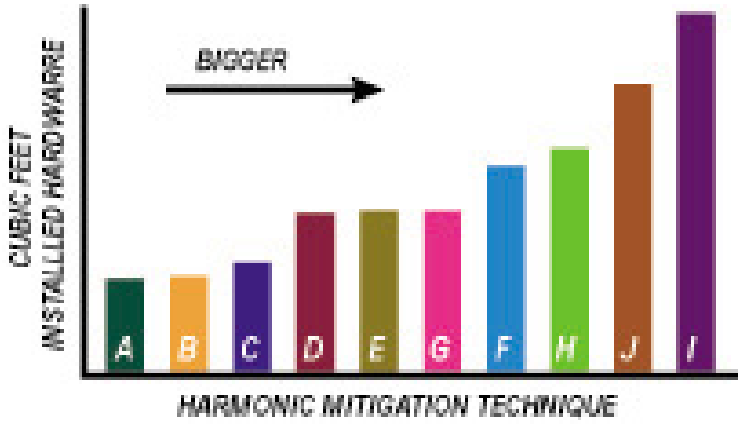


Harmonic Mitigation:

Comparisons

Performance Charts





Legend

A. 6-pulse, no link choke

B. 6-pulse, with link choke

C. Input line reactor

D. Tuned and non-tuned filters

E. 12-pulse with auto transformer

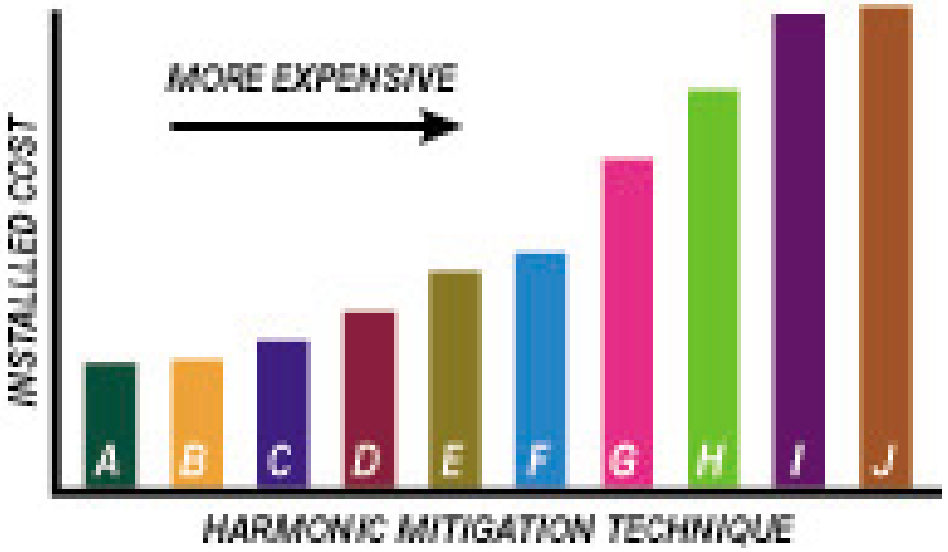
F. 12-pulse with isolation transformer

G. 18-pulse with auto transformer

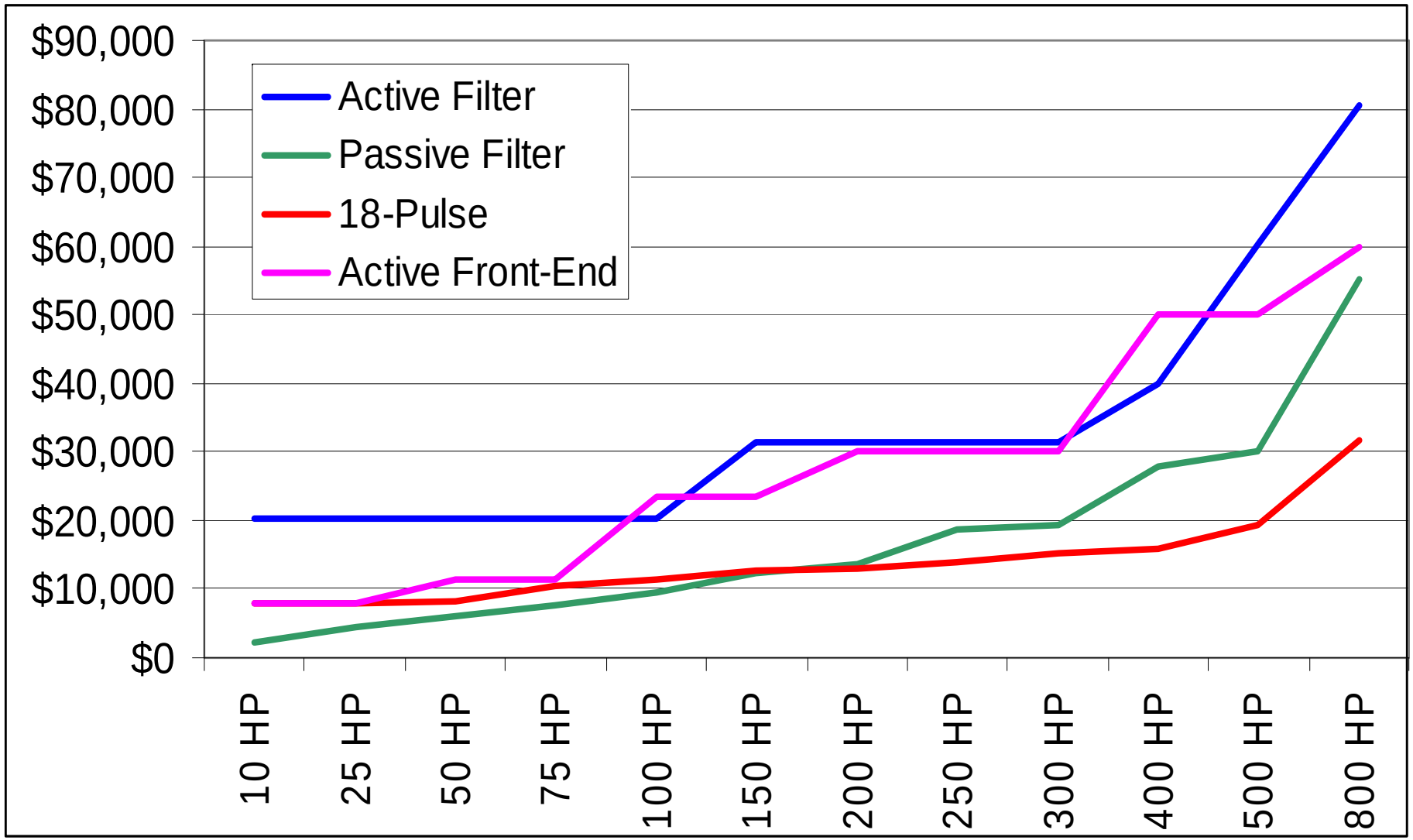
H. 18-pulse with isolation transformer

I. Regenerative active front end

J. Active power filter



Harmonic Mitigation Comparisons - Costs



Solutions Check-List

Harmonic Mitigation Solutions Check-List	6-Pulse Drive	18-Pulse Drive	Passive Filter	Active Filter	Active Front-End
Typical Ithd	20 - 45%	4.5 - 6%	5 - 8%	3 - 5%	3 - 5%
Meet IEEE Special Applications	No ✗	Yes ✓	Marginal	Yes ✓	Yes ✓
Meet IEEE General Applications	No ✗	Yes ✓	Yes ✓	Yes ✓	Yes ✓
Meet IEEE Dedicated Applications	Yes ✓	Yes ✓	Yes ✓	Yes ✓	Yes ✓
Effect of 1% Voltage Unbalance	Large ✗	Moderate	Minimal ✓	Minimal ✓	Minimal ✓
Potential Low DC Bus	No	No	Yes ?	No	No
Potential System Resonance	No	No	Yes ?	No	No
Typical Total Power Factor, no / full load	0.75 - 0.95	0.90 - 0.99 ✓	0.3 - 1 lead ?	0.90 - 0.99 ✓	0.8 - 1 lead
Efficiency	97% ✓	96.5% ✓	96.5% ✓	96%	96 - 97.5%
Cost Effective	Good ✓	>150hp ✓	<150hp ✓	Large Sys	Regen, MV
Overall Size (relative to 6-P Drive)	1.0	3.3	2 - 6	3.5 - 5	1.5 - 2.5 ✓
Reliability	High ✓	High ✓	Medium	Medium	Medium

✓ Good

? Need to confirm application

✗ May not meet IEEE 519

Questions?

ALLEN-BRADLEY • ROCKWELL SOFTWARE • DODGE • RELIANCE ELECTRIC

Rockwell Automation

Wrap-Up

Practical Aids for Harmonic Compliance

- Take time to understand the benefits and drawbacks of each type of mitigation solution to assure you meet the requirements of the application and that you can live with any negative effects created by the chosen harmonic solution.
- Identify the required PCC and apply techniques most cost effective for that location.
- Perform a preliminary harmonic analysis and explore the effects of using various harmonic mitigation methods.
- Add a line reactor (or DC link choke if possible) to any un-buffered 6-pulse drive or group of drives.

Practical Aids for Harmonic Compliance

- Design the system to isolate linear and non-linear loads and create two systems with 5% and 10% voltage limits.
- For passive filters on generator power, select a filter with a dropout contactor terminal block for the filter capacitors. This will limit the leading power factor under no-load operation and stand-by operation.
- Never use power factor correction capacitors at the input (or output) of a drive.

Practical Aids for Harmonic Compliance

- Consider use of an active filter on a multiple drive system or MCC lineup to correct for harmonic distortion.
- Consider an active front end if the application requires regenerative operation and harmonic compliance.
- When conducting a drives-based harmonic analysis, establishing the PCC at any point other than where the sharing of utility power occurs is not consistent with the intent of IEEE519-1992 and may lead to the purchase of unnecessary equipment.

Market Trends

- The 18 Pulse market is firmly established.
- Passive filter are evolving. Recent new designs have surfaced with very good performance. System resonance with multiple filters needs investigation. Suitable for smaller horsepowers <100
- Active Filters are technically viable but *right now* are a more costly solution for most projects.
- Active Filters fare better on large projects with the PCC specified at transformer secondary.
- The price of copper and iron is going up while the price of power electronics is coming down.

Questions?

ALLEN-BRADLEY • ROCKWELL SOFTWARE • DODGE • RELIANCE ELECTRIC

Rockwell Automation