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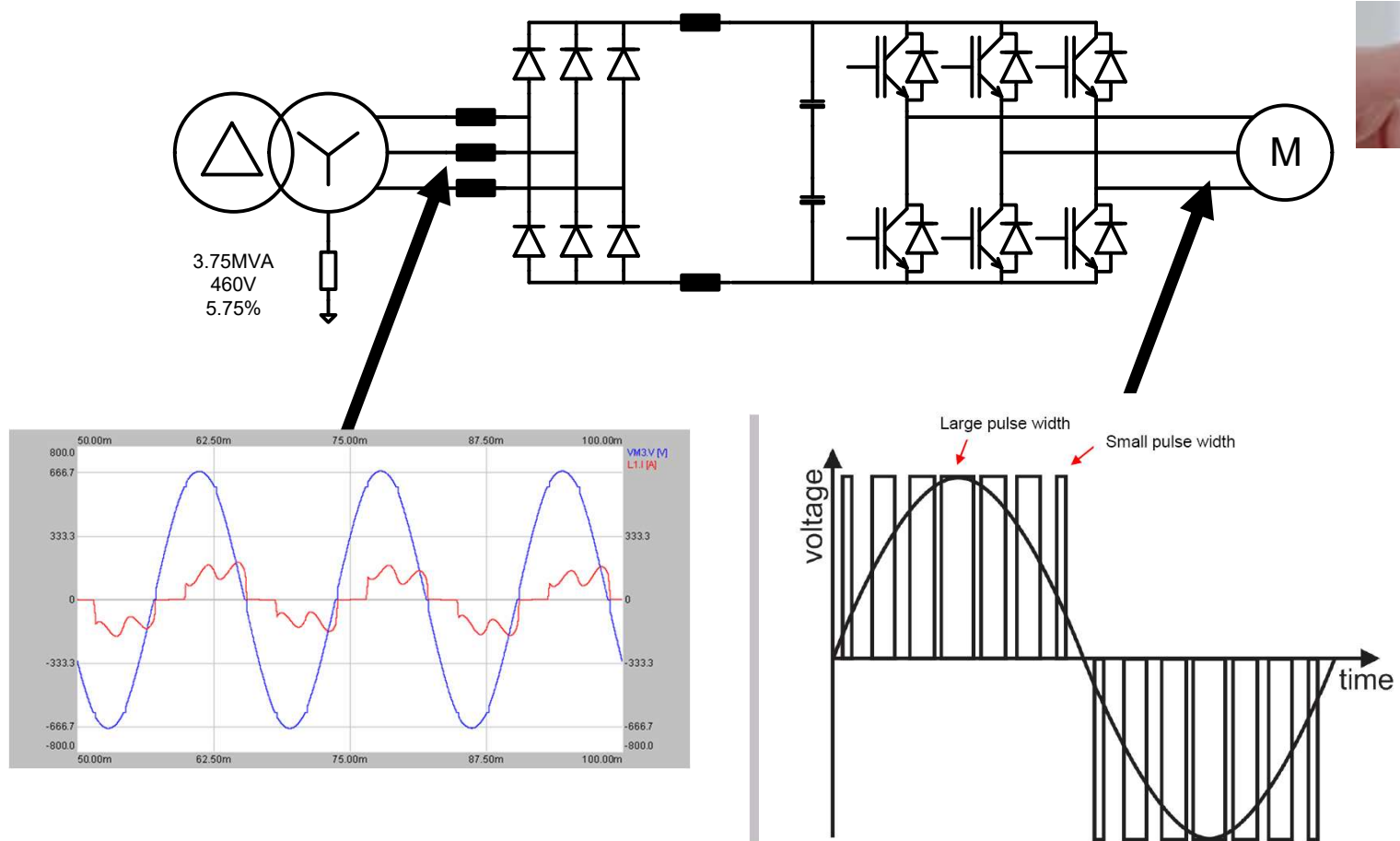
Understanding Harmonics

Thomas Svoren- Sr.Consultant Eng
Rockwell Automation



PUBLIC

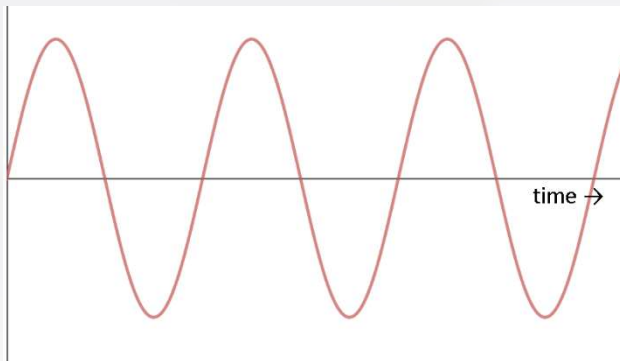
What a VFD input/output voltage and current looks like



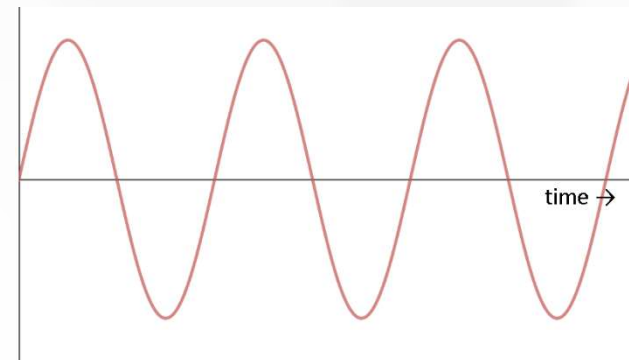
PUBLIC

Linear Voltage and Current

Voltage



Current



Examples of Linear Loads

- Induction motors
- Incandescent lights
- Resistance heaters
- Power Factor Correction Caps
- Electromagnetic devices
 - Transformers
 - non-linear
 - During energization
 - Over-voltage

Examples of Non-Linear Loads

Single Phase

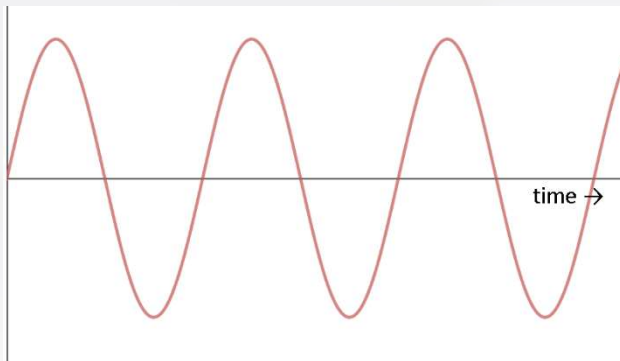
- Fluorescent lights (ballast)
- Incandescent lights with light dimmers
- Anything with an ac-dc power supply
 - Computers (ac-dc PS)
 - Monitors (ac-dc PS)
 - TVs (ac-dc PS)
 - Fax machines (ac-dc PS)

Three Phase

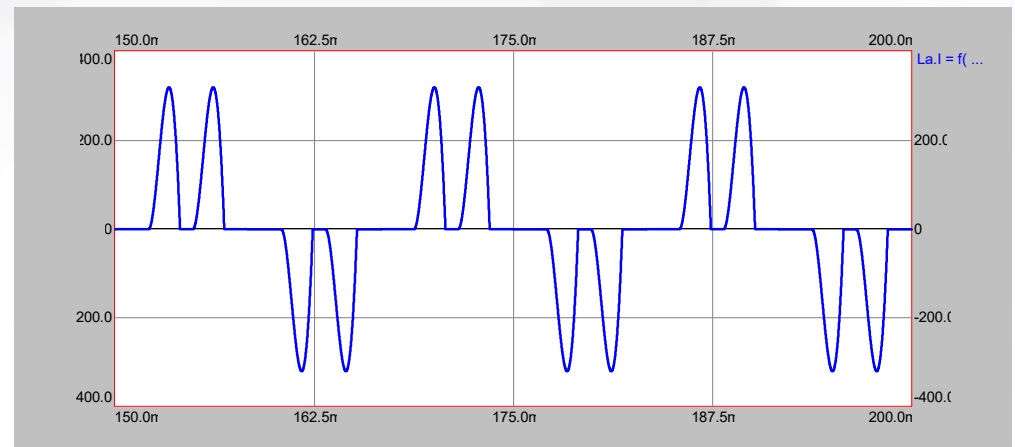
- Welders
- Arc furnaces
- UPS
- DC power supplies
- DC Drives
 - Phase control
 - PWM
- **AC Drives**
 - **6-Step**

Non-Linear Voltage and Current

Voltage

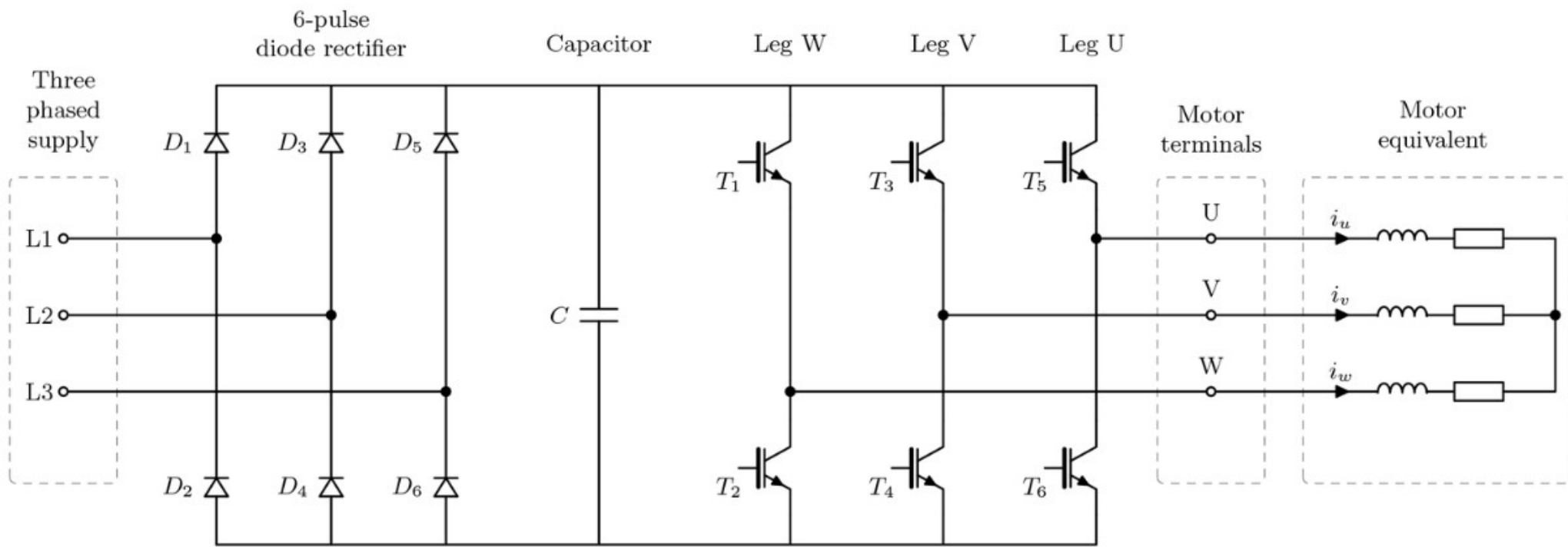


Current

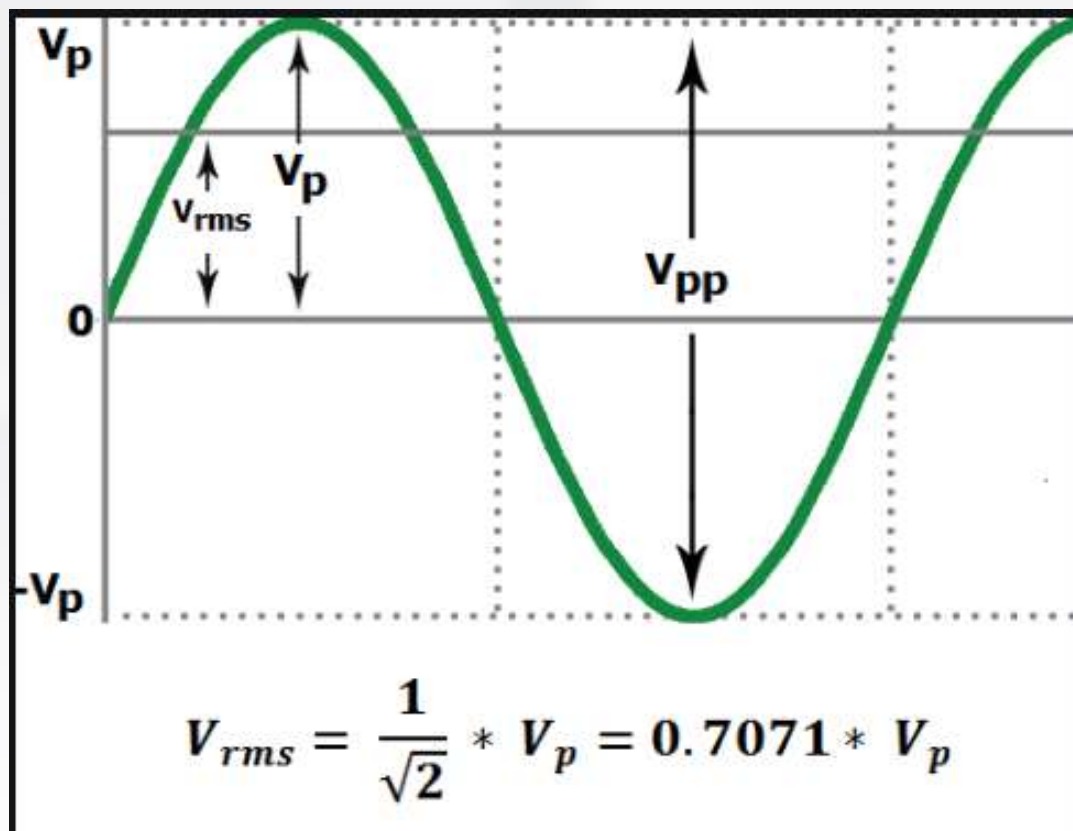


Power Structure of the Component Class Drive

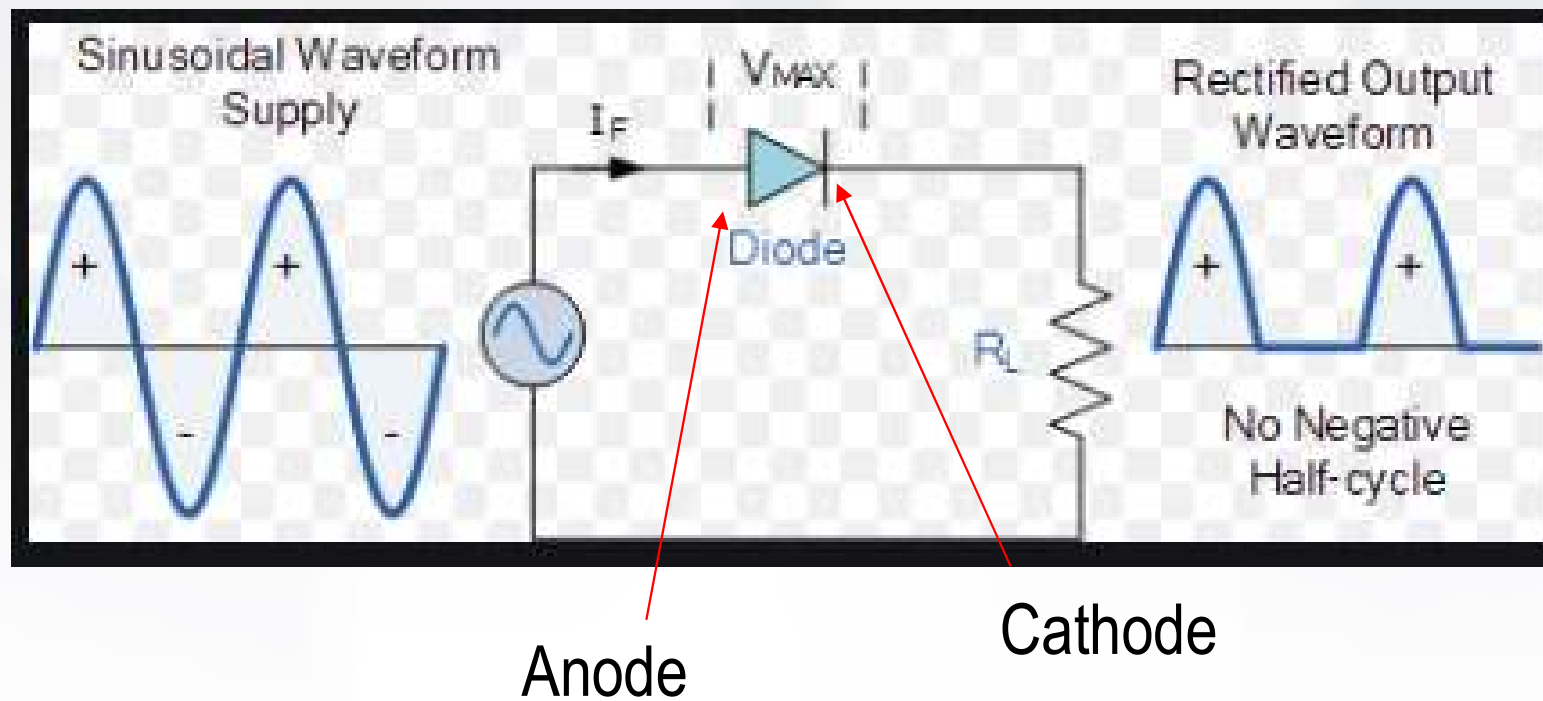
(Most Powerflex 4 and 5 class)



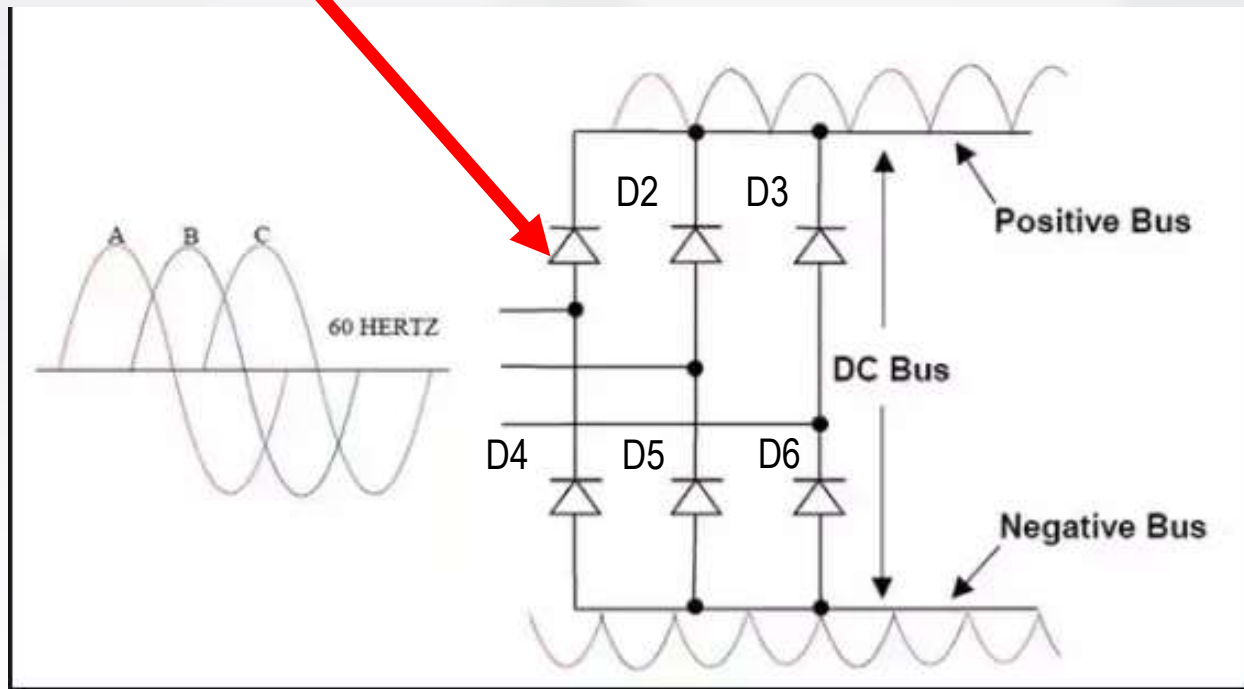
Voltage Applied



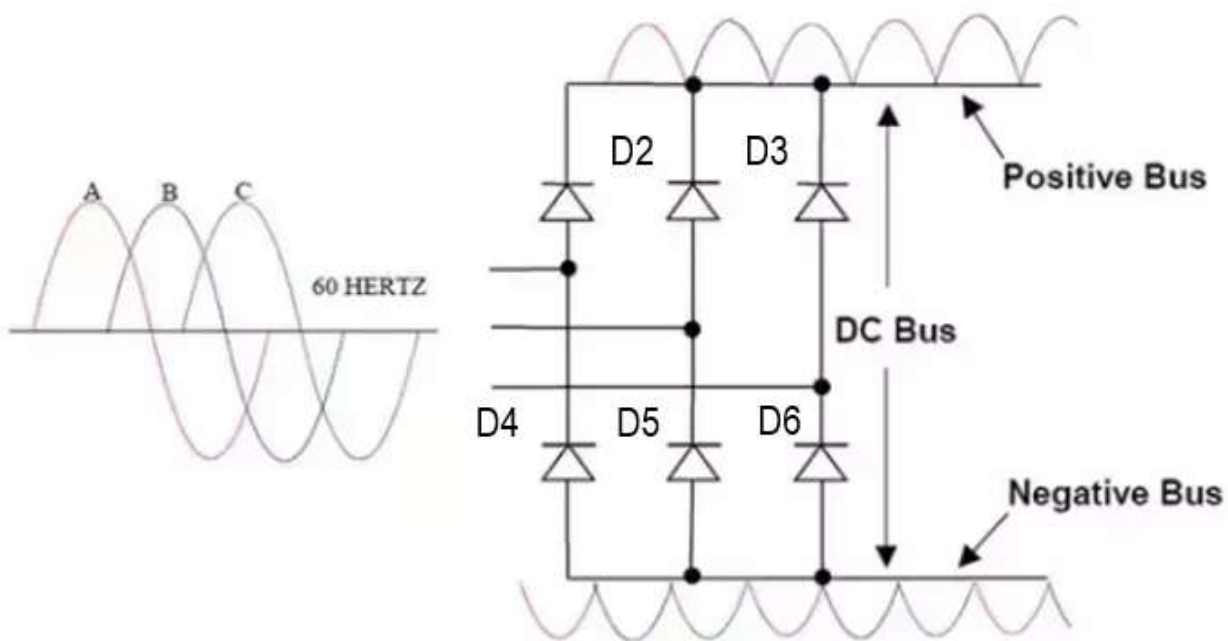
When does a diode conduct?



When does D1 Conduct?



When does D1 Conduct?



D1-D5

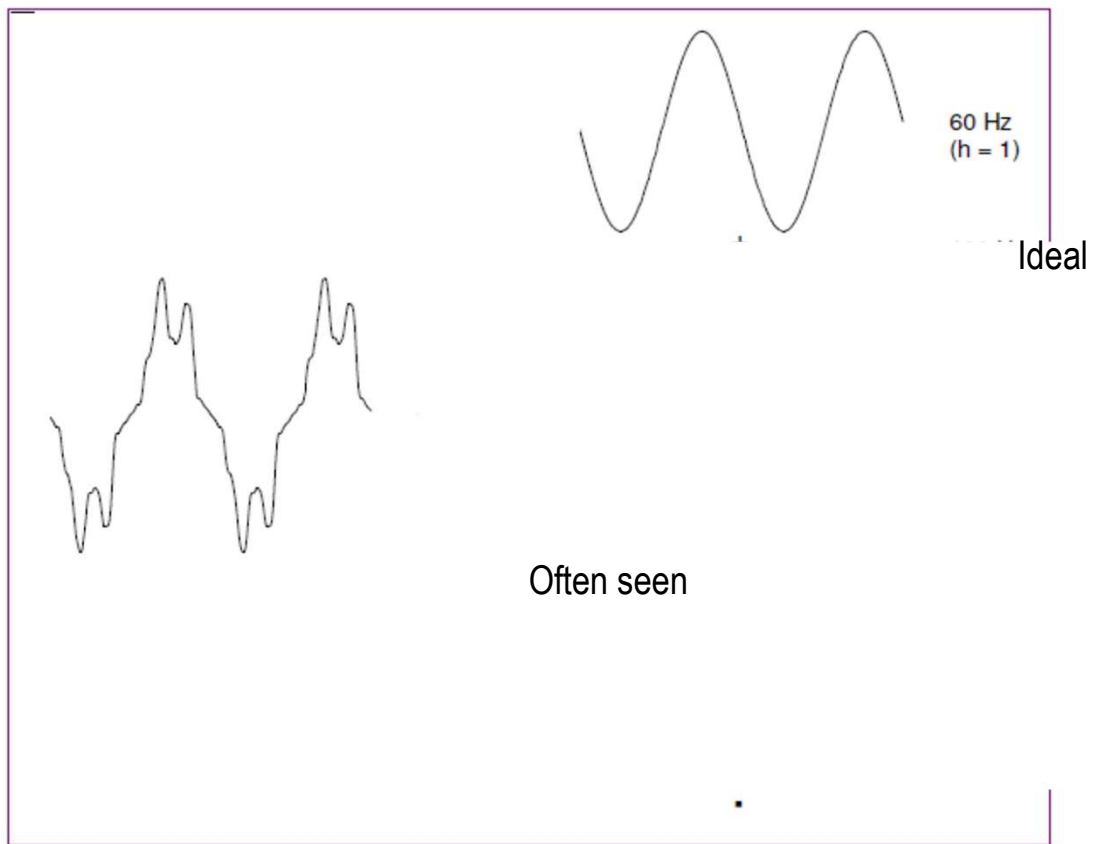
D1-D6



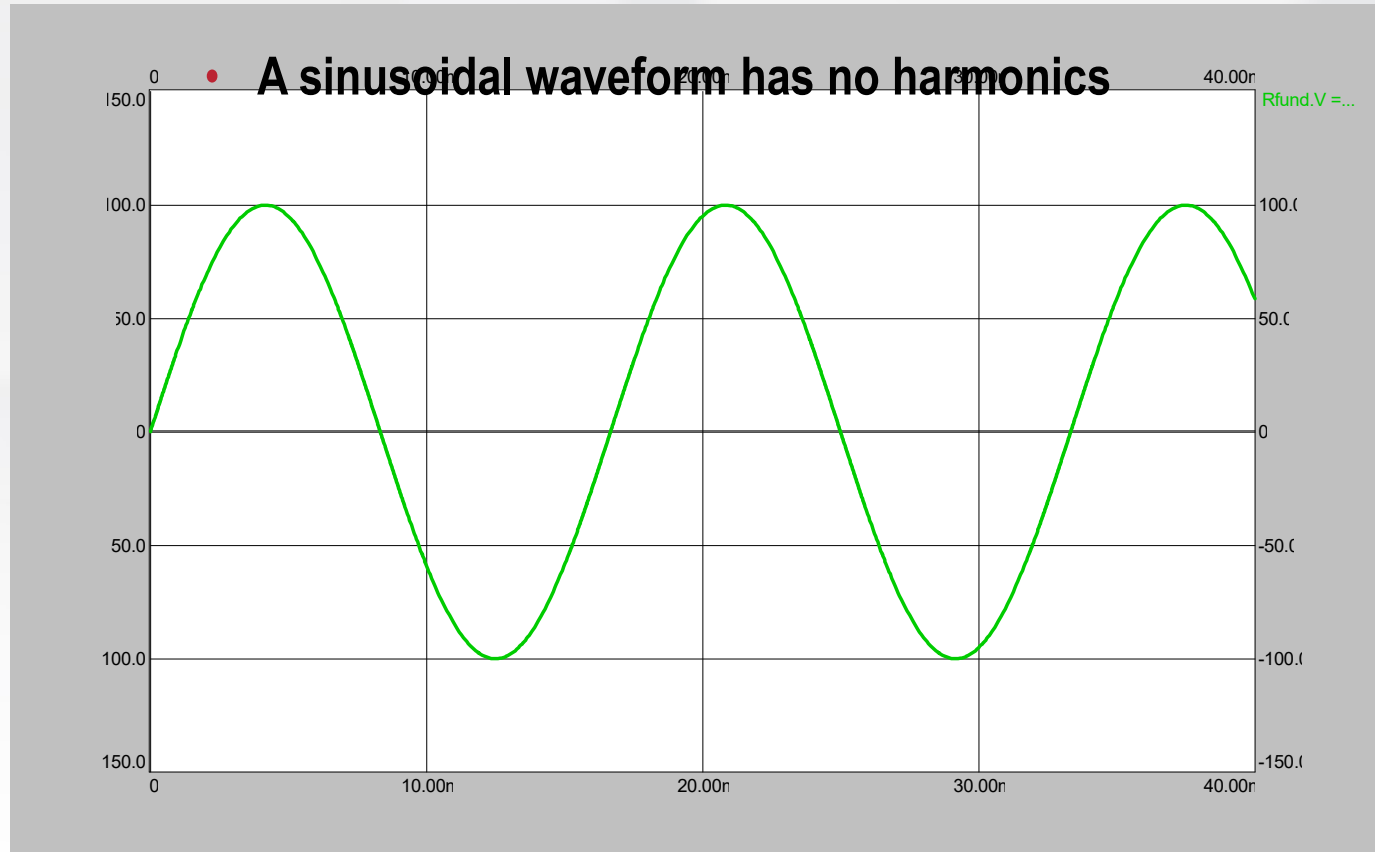
D4-D2

D4-D3

What Are Harmonics?

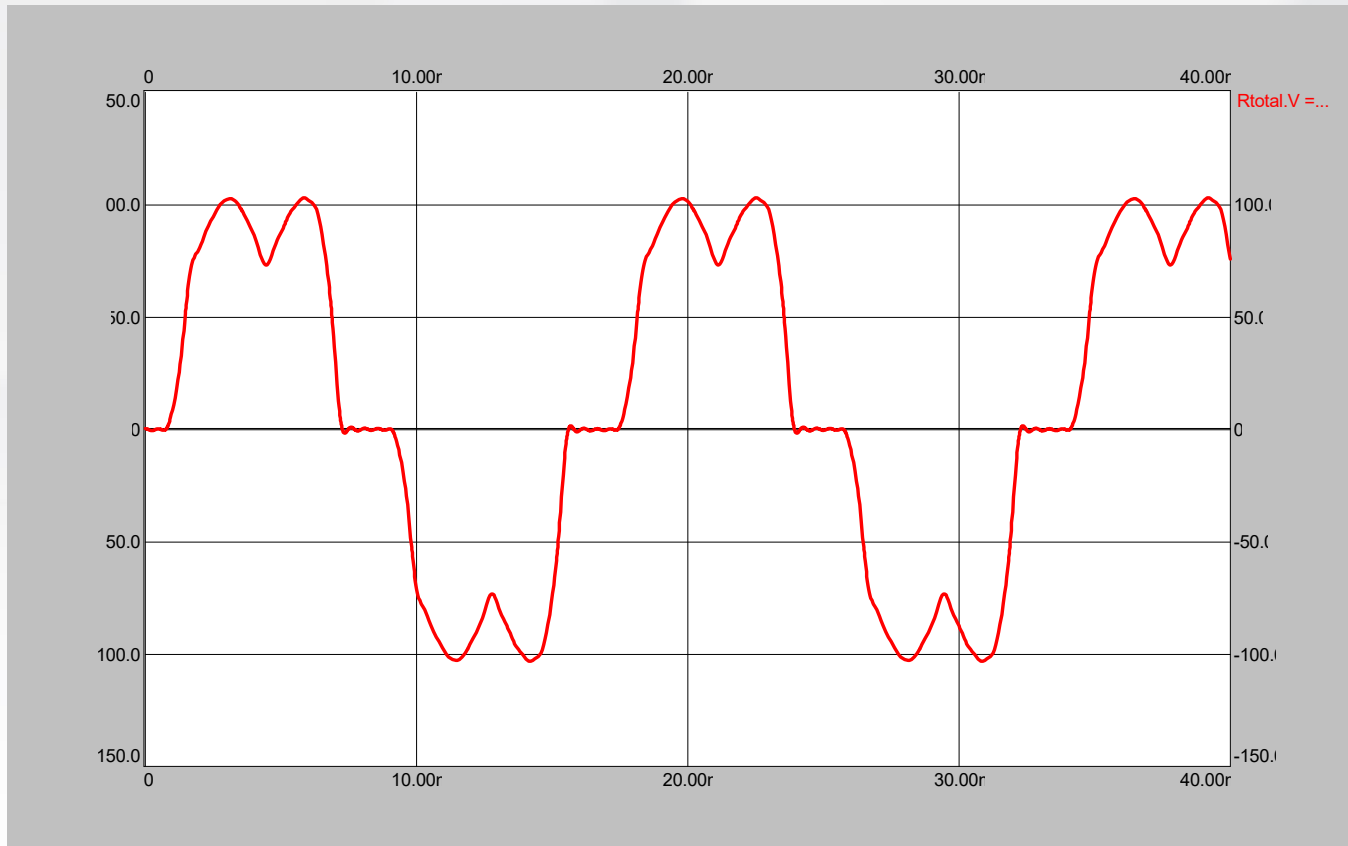


What are Harmonics? What are waveforms?



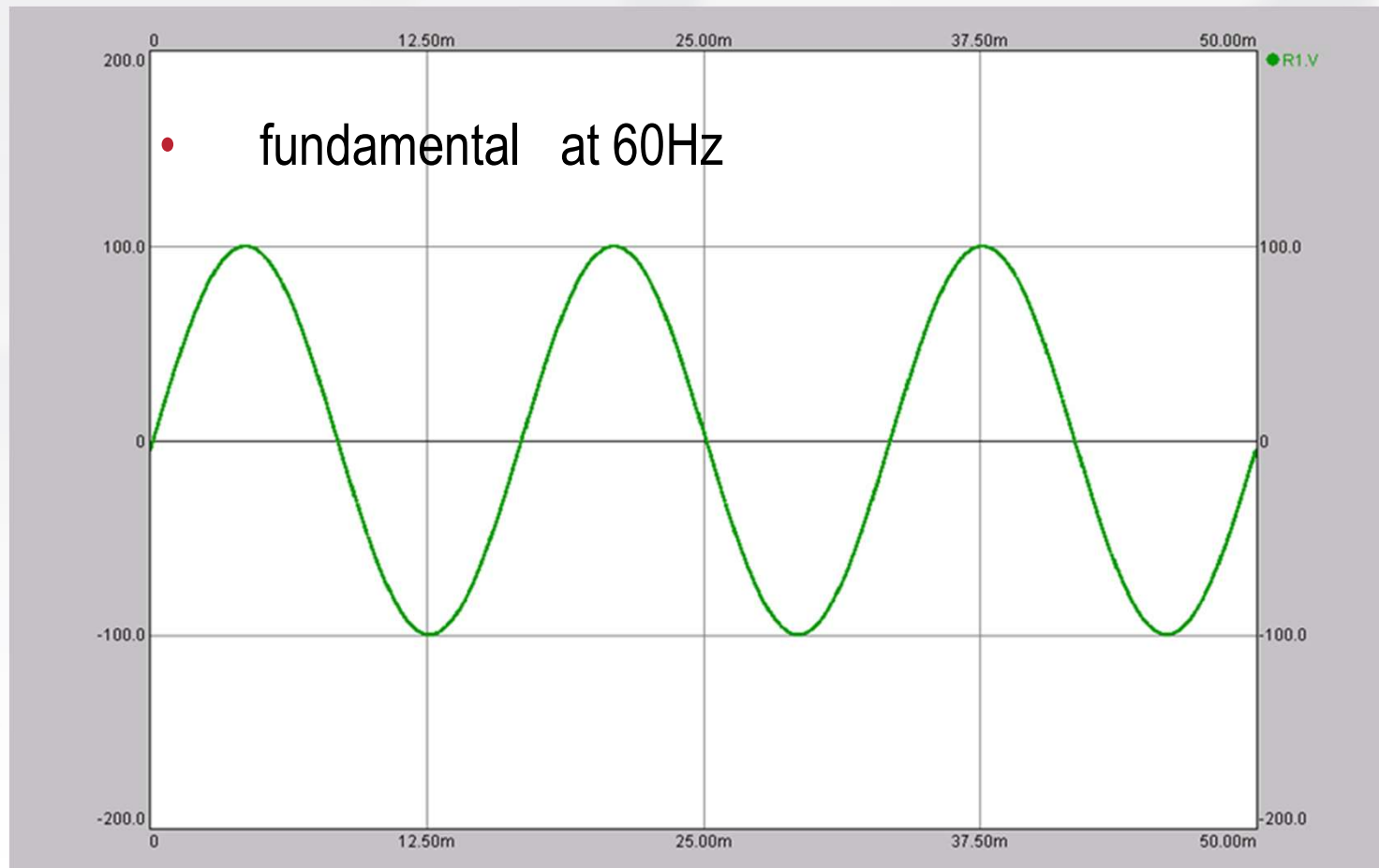
What are Harmonics and Waveforms

- This non-sinusoidal waveform contains harmonics



Let's create a distorted waveform

Fundamental (1st harmonic) Only



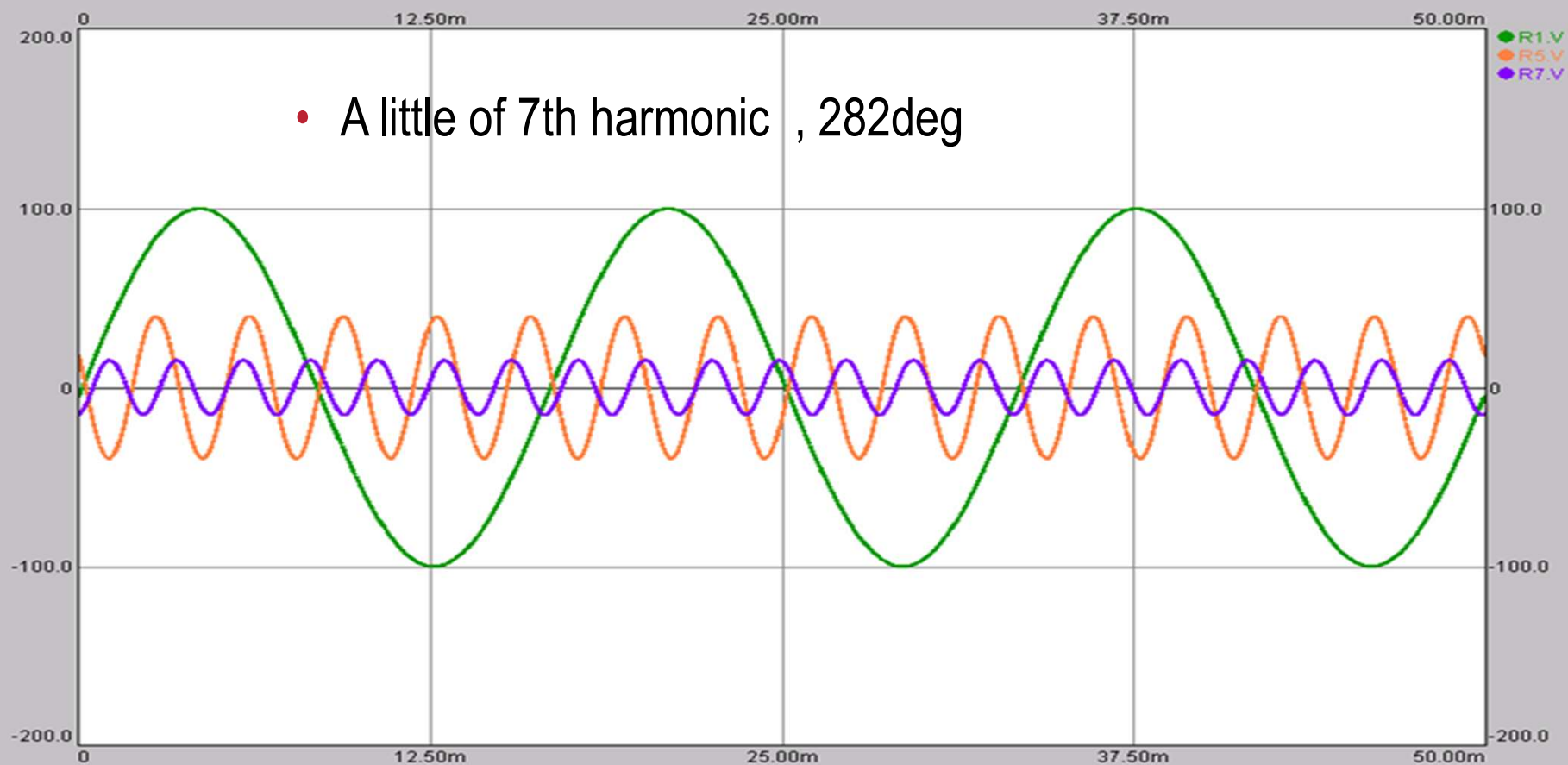
Fundamental and 5th Harmonic

- Some 5th harmonic , 153deg



1st, 5th and 7th Harmonics

- A little of 7th harmonic , 282deg



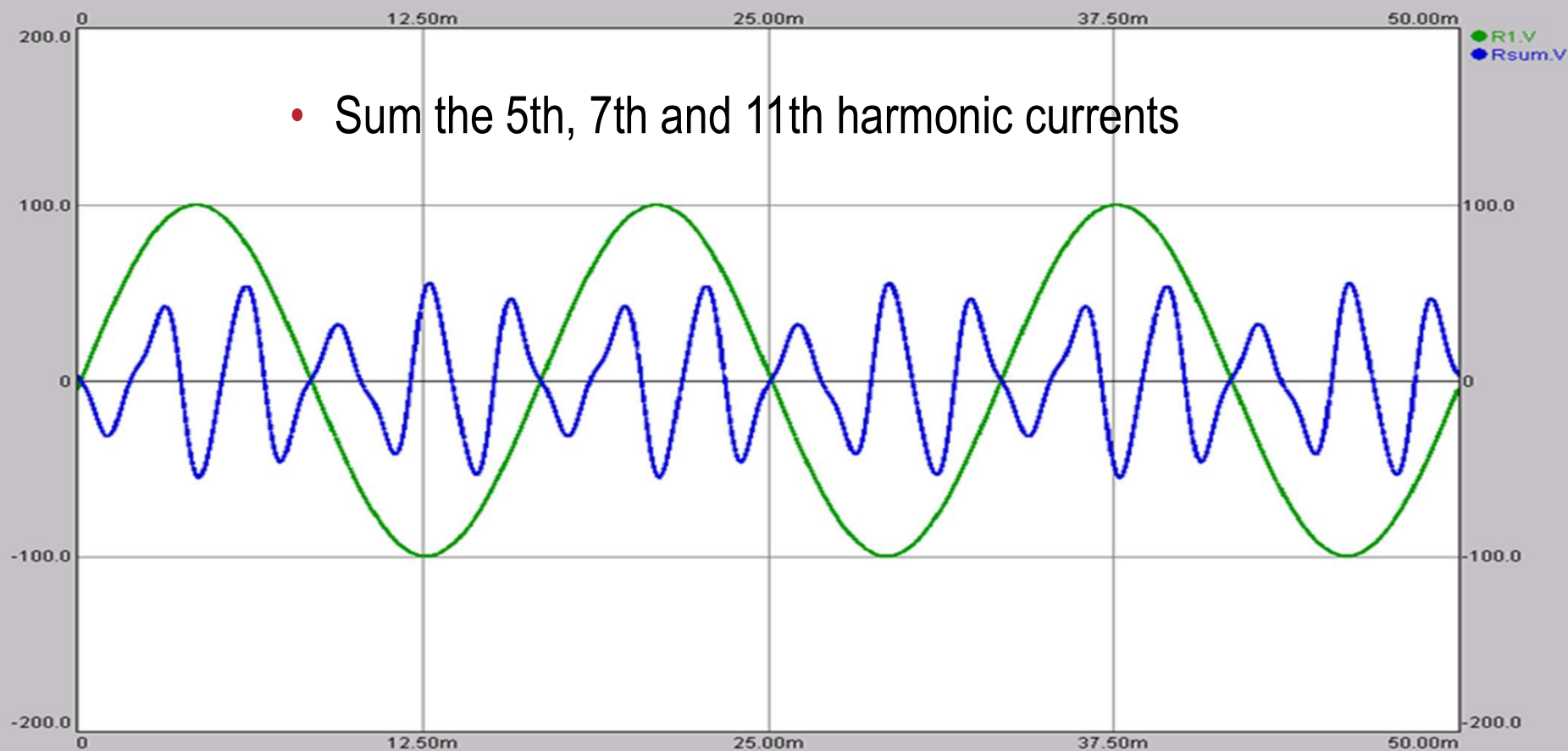
1st, 5th, 7th and 11th Harmonics

- A bit of 11th harmonic , 0deg



1st and Sum of the 5th, 7th and 11th

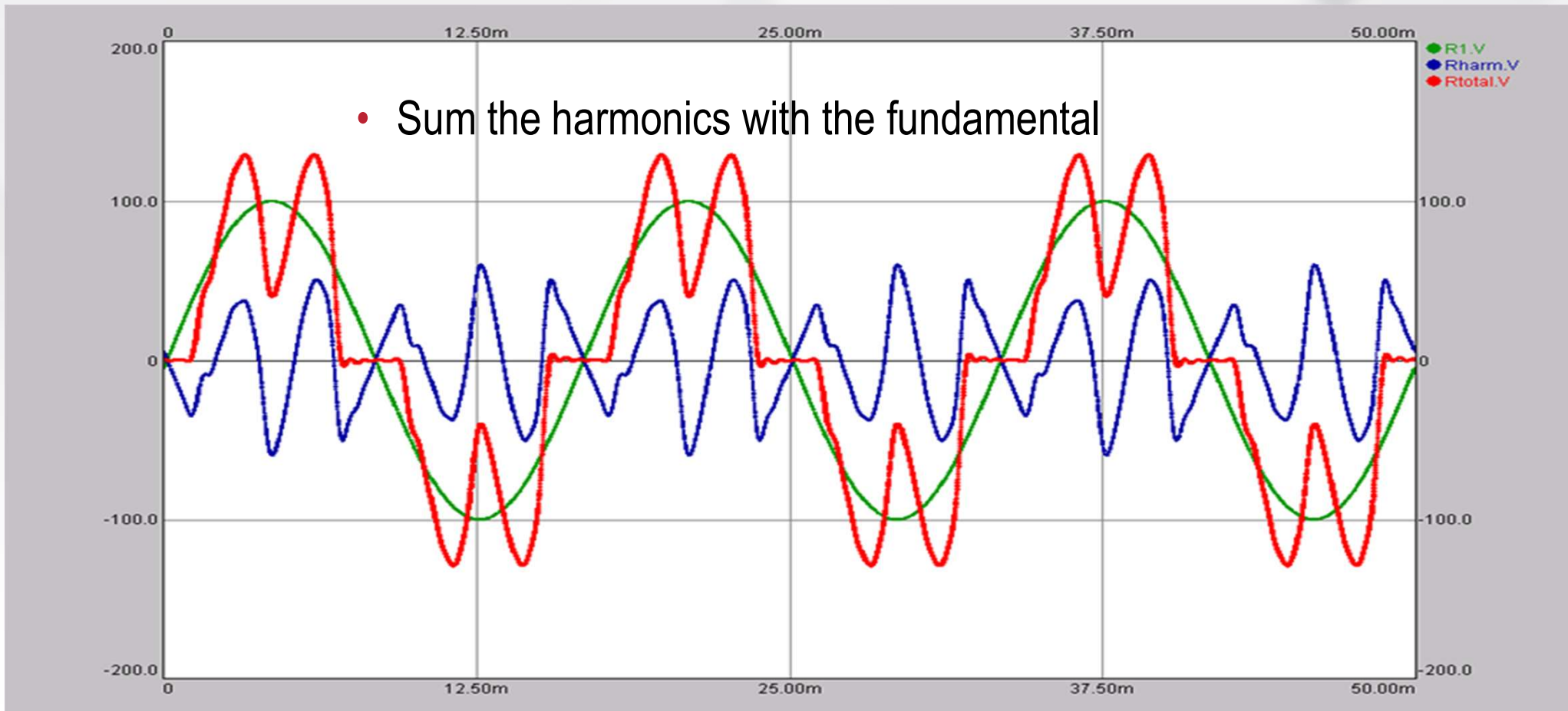
- Sum the 5th, 7th and 11th harmonic currents



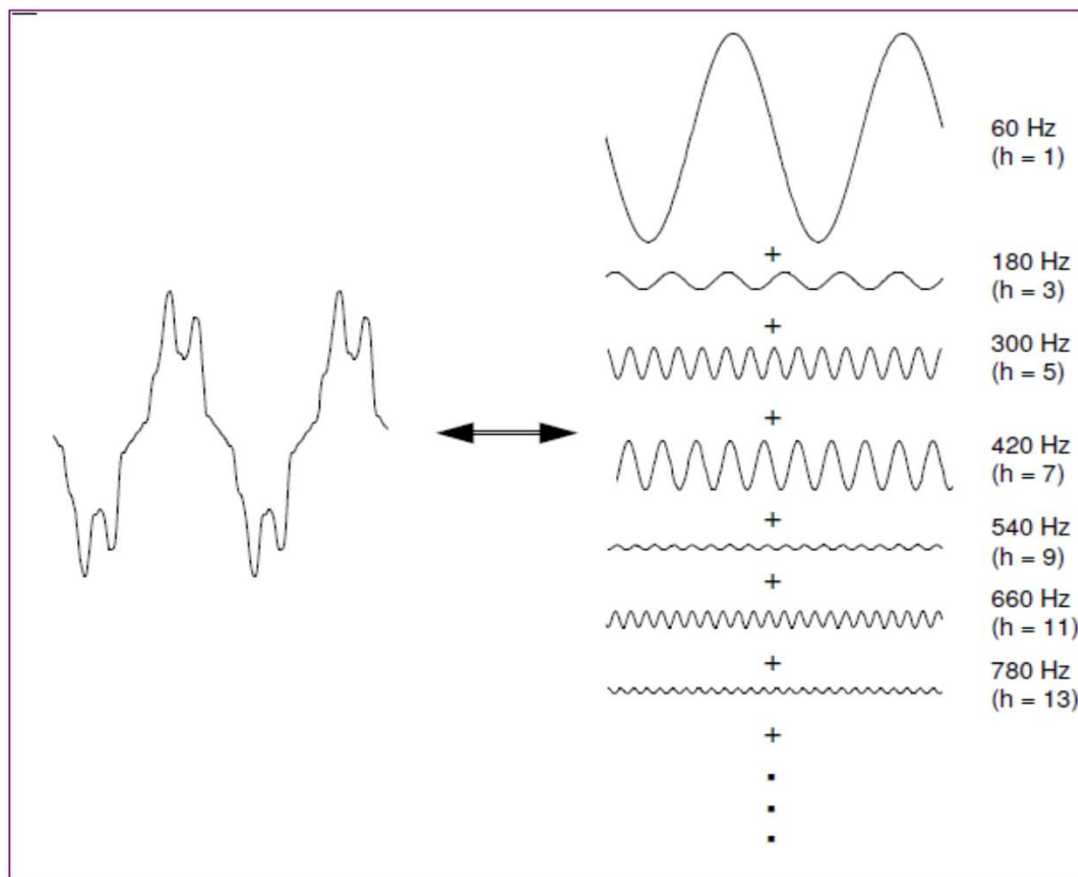
Why are you talking about the 5th, 7th and 11th harmonic? Seems arbitrary.

- Rules for which Harmonics matter:
 - Only odd harmonics (even harmonics cancel out)
 - Harmonics that are not divisible 3. Meaning no 3rd, 6th, 9th etc.
 - $P * n +/- 1$ Where P is the number of pulse of the bridge
n is a whole number and constant

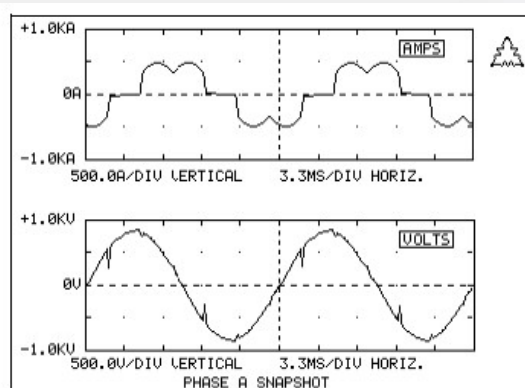
Fundamental, Harmonics, Total



What Are Harmonics?



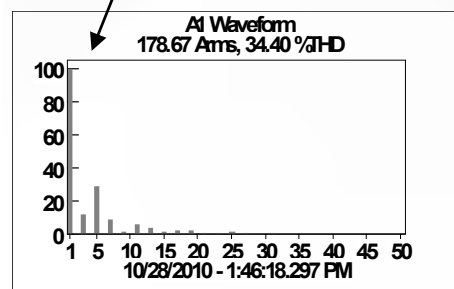
FFT (Fast Fourier Transform) and how are Harmonics measured?



PHASE A CURRENT SPECTRUM 2:51:53 PM
Fundamental amps: 346.2 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	-43°	2nd	0.3%	68°
3rd	0.4%	-126°	4th	0.2%	30°
5th	25.3%	-30°	6th	0.1%	61°
7th	5.5%	-122°	8th	0.2%	10°
9th	0.6%	37°	10th	0.2%	-45°
11th	8.2%	-102°	12th	0.1%	-37°
13th	3.9%	170°	14th	0.2%	-65°
15th	0.3%	-40°	16th	0.2%	-119°
17th	5.0%	-179°	18th	0.1%	-126°
19th	2.9%	93°	20th	0.2%	-136°
21st	0.3%	-44°	22nd	0.2%	167°
23rd	3.4%	109°	24th	0.1%	162°
25th	2.1%	14°	26th	0.2%	150°
27th	0.2%	-144°	28th	0.2%	100°
29th	2.7%	39°	30th	0.1%	86°
31st	1.9%	-59°	32nd	0.2%	74°
33rd	0.2%	99°	34th	0.2%	29°
35th	2.1%	-35°	36th	0.1%	6°
37th	1.7%	-135°	38th	0.2%	3°
39th	0.3%	41°	40th	0.2%	-42°
41st	1.6%	-110°	42nd	0.2%	-72°
43rd	1.5%	150°	44th	0.2%	-70°
45th	0.5%	-30°	46th	0.2%	-114°
47th	1.7%	177°	48th	0.2%	-146°
49th	1.4%	70°	50th	0.2%	-142°
ODD	28.9%		EVEN	1.0%	
THD:	28.9%				

Harmonic
Power Meter
Performing FFT



Power Source



AC Drive



Motor

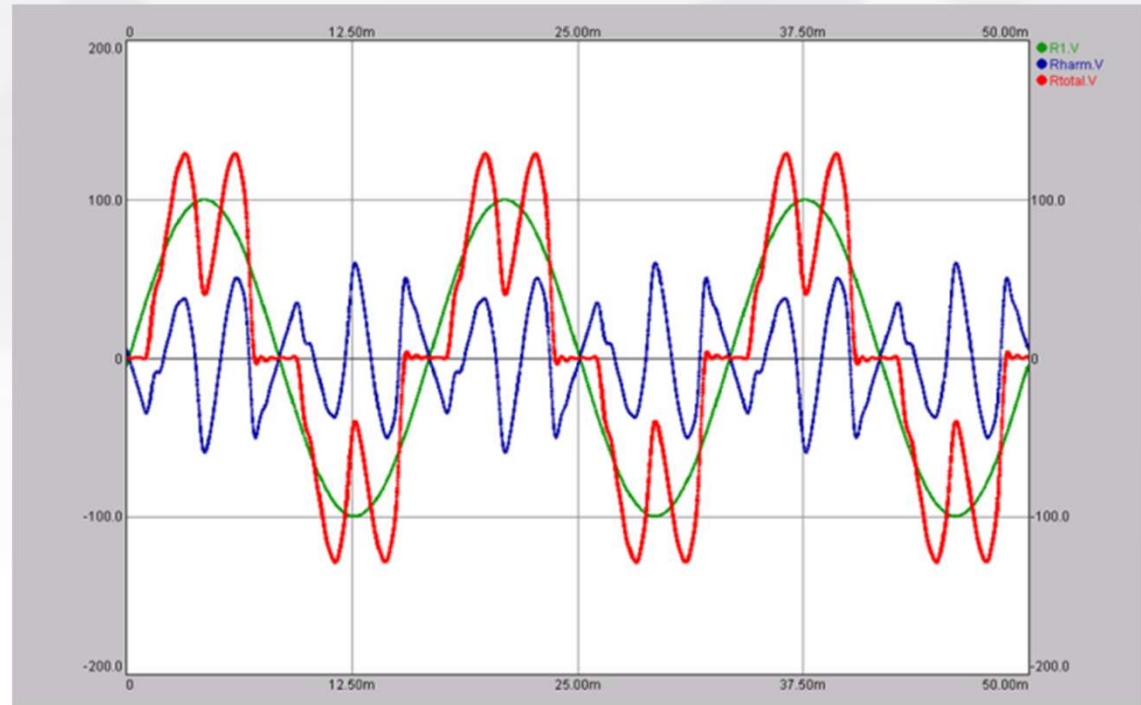
THD (Quantifying Harmonics)

$$I_{\text{harm}} = 30.83\text{A}$$

$$I_{\text{fund}} = 70.71\text{A}$$

$$I_{\text{total}} = 77.14\text{A}$$

$$I(\text{THD}) = 43.6\%$$
$$= I_{\text{harm}} / I_{\text{fund}}$$



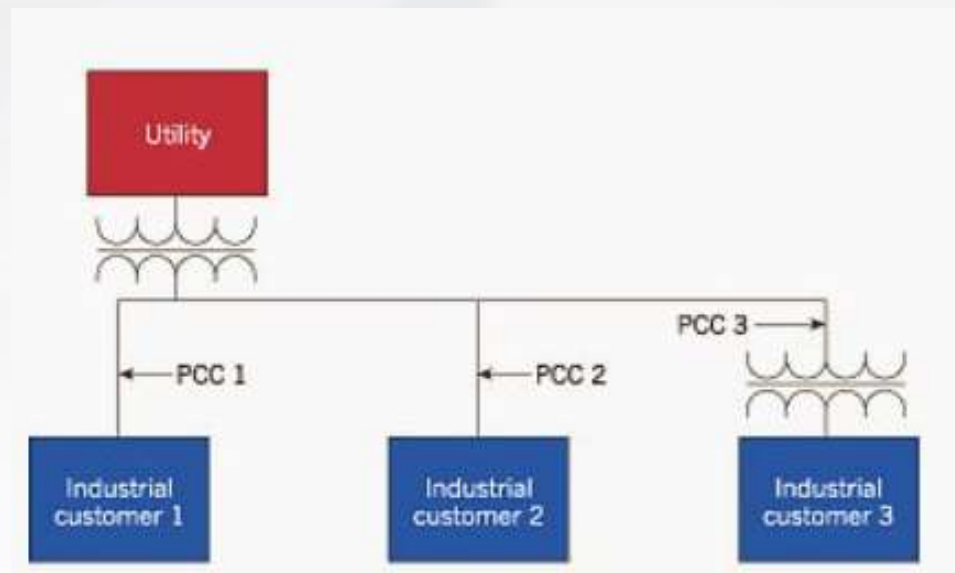
What Is I(THD)?

- $I(\text{THD}) = I_{\text{harm}} / I_{\text{fund}}$
- So, $I_{\text{harm}} = I(\text{THD}) * I_{\text{fund}}$
- $I(\text{THD})$ is a ratio between two numbers, it does not stand alone!

We can **decrease** $I(\text{THD})$
by either **decreasing** I_{harm} or **increasing** I_{fund}

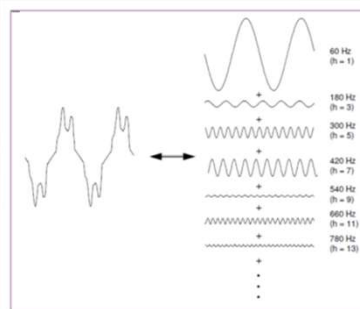
Where you measure Harmonics...

Point of Common Coupling (PCC)



What do Harmonics do anyway?
Why do we care?

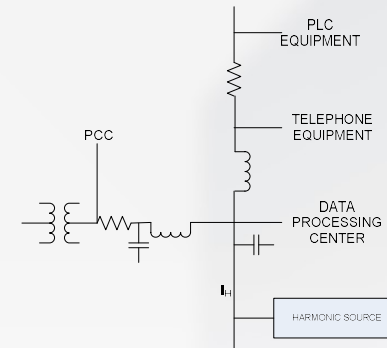
Current Harmonics



create

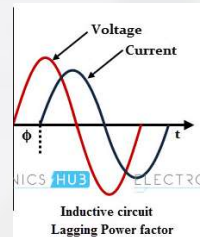
Voltage Distortion

Heat



What other problems do they cause?

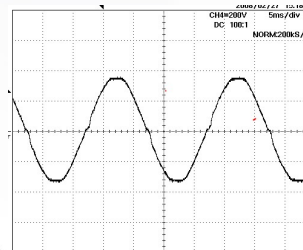
- Increased Utility current



- Component overheating

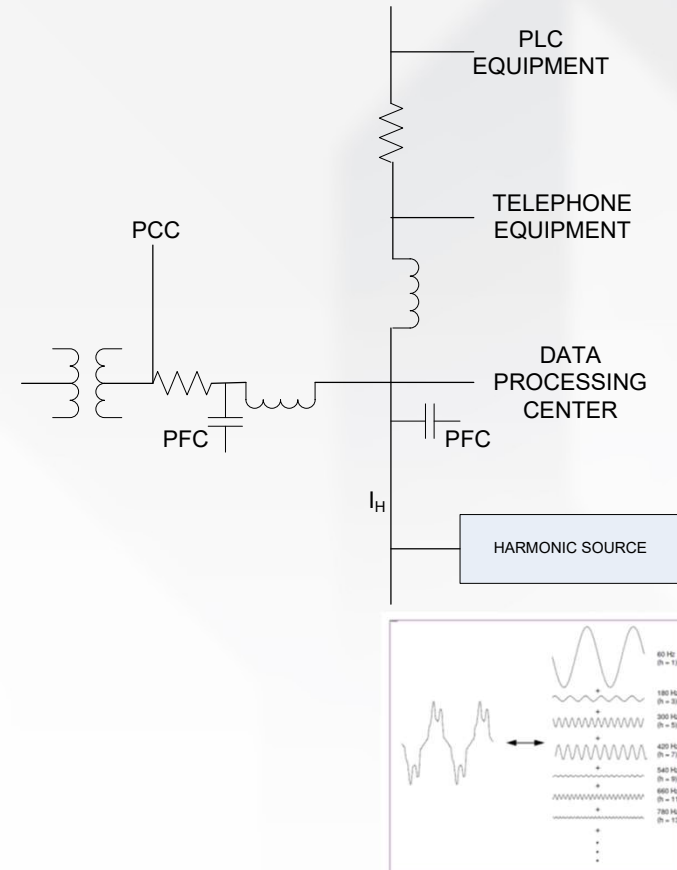


- Equipment malfunction

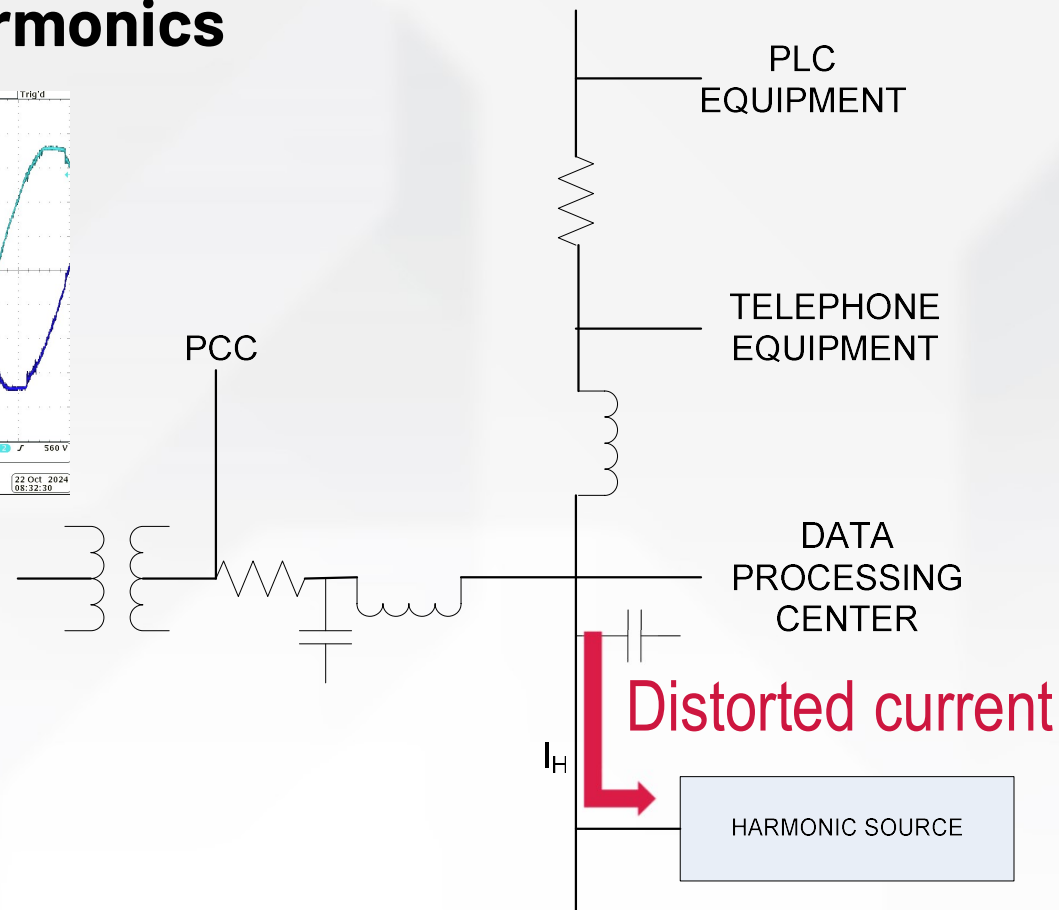
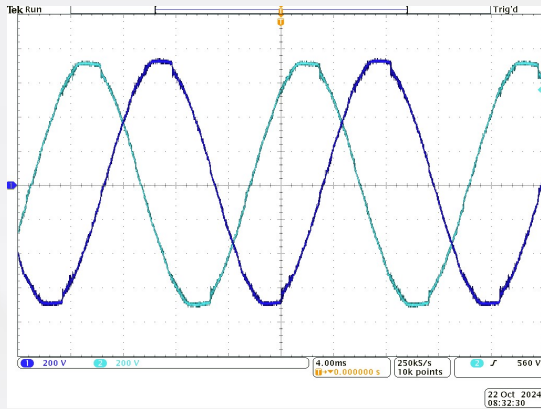


- Excitation of Power System Resonance's creating over-voltage's

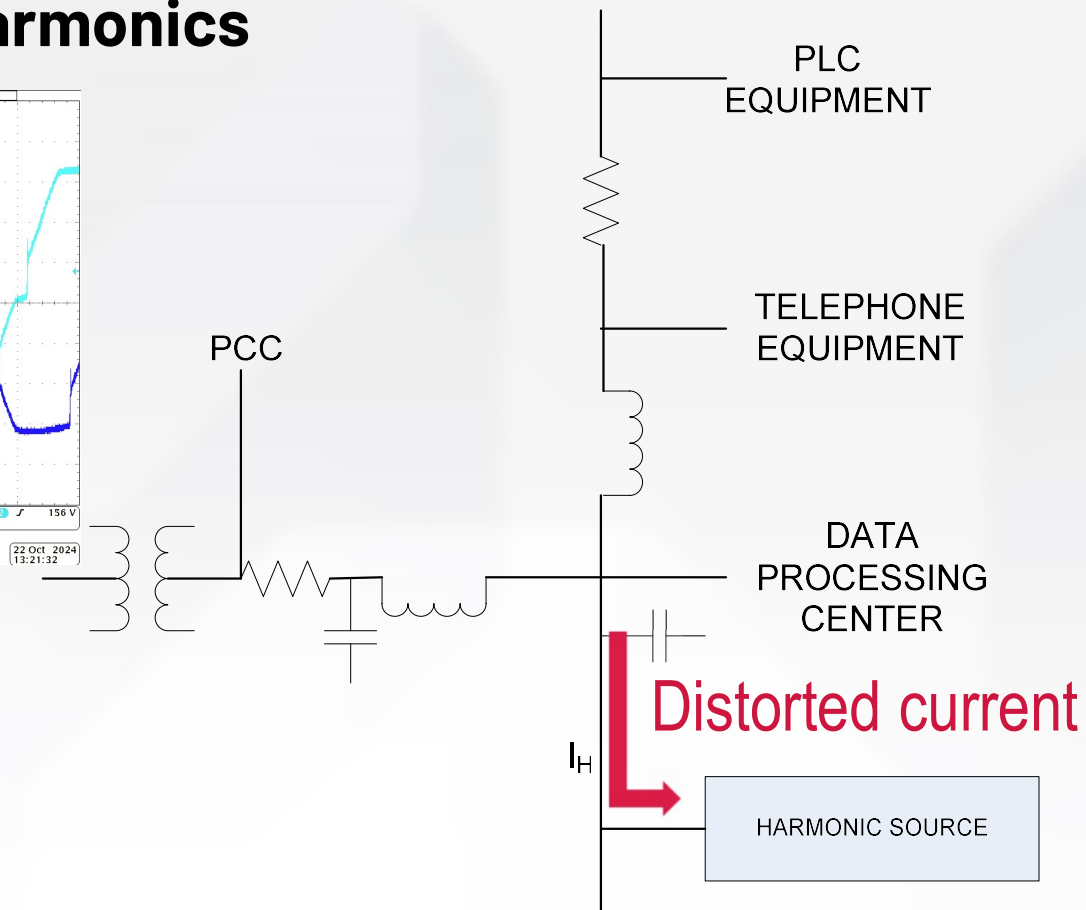
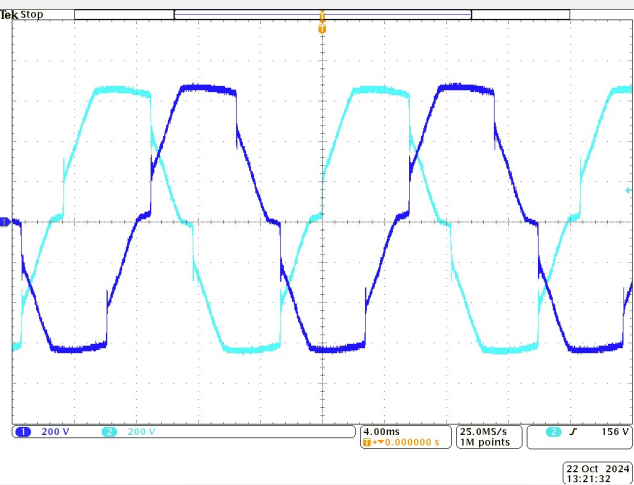
- If PFCC in system



Main Point on Harmonics



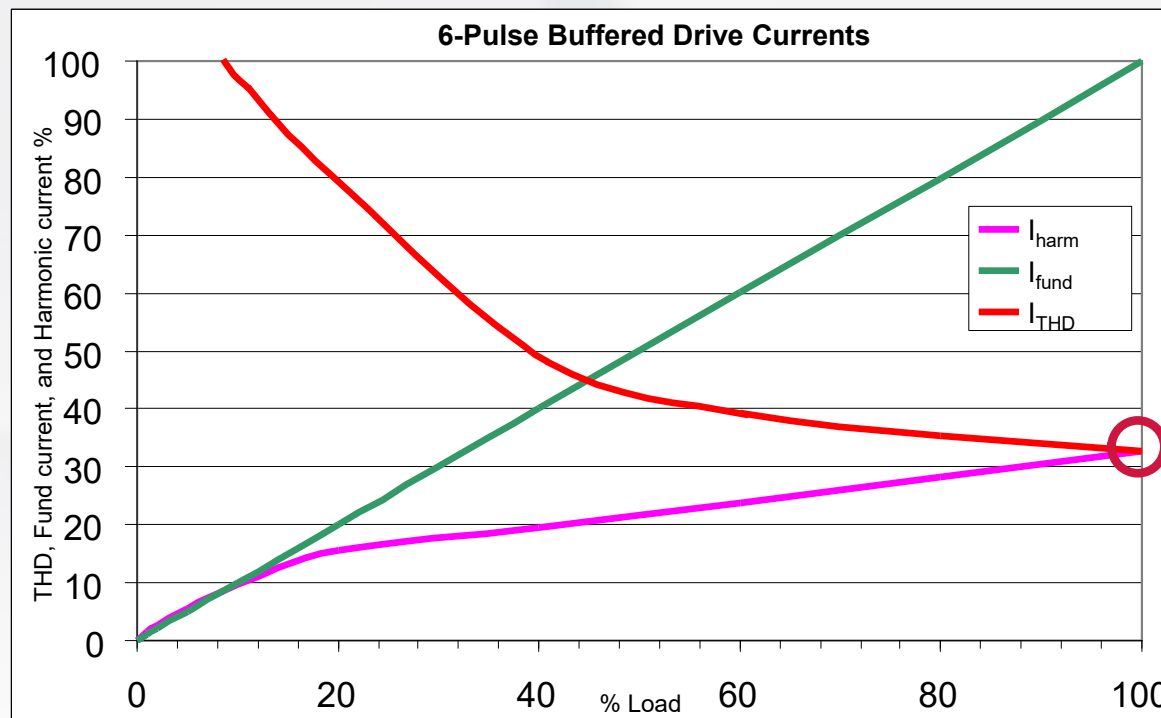
Main Point on Harmonics



When should you be concerned about Harmonics?

- When Voltage Distortion exceeds 8%
- If service Transformer is Loaded near rating 60%
- 20 % of total Transformer rated current is Non-Linear electronic load
- When PF correction capacitors Used or Planned

How Does Motor Load Affect I_{THD} ?



I_{TDD}

NOTES:

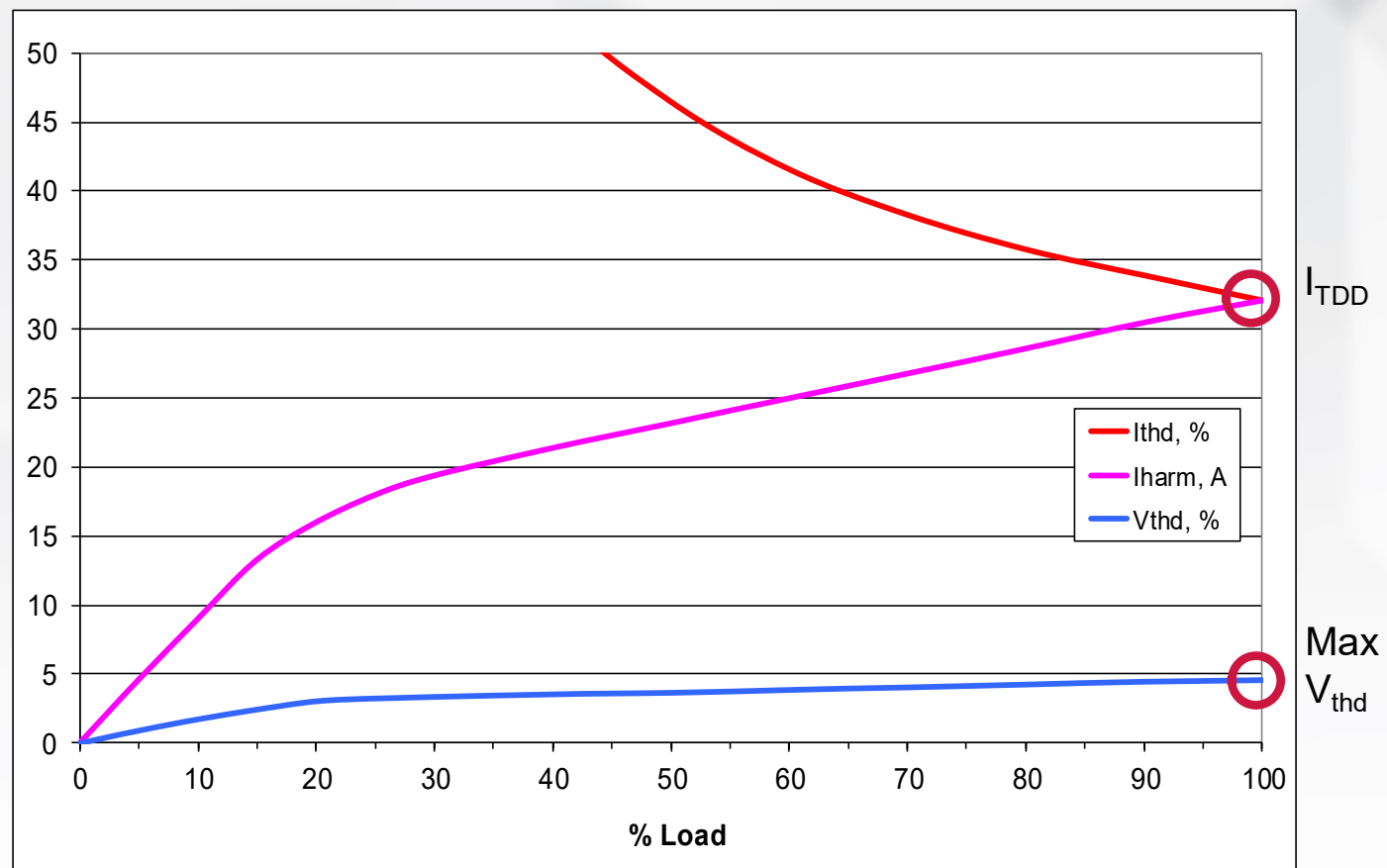
$$I_{THD} = I_{harm} / I_{fund}$$

I_{THD} **increases** as load decreases

I_{fund} **decreases** as load decreases

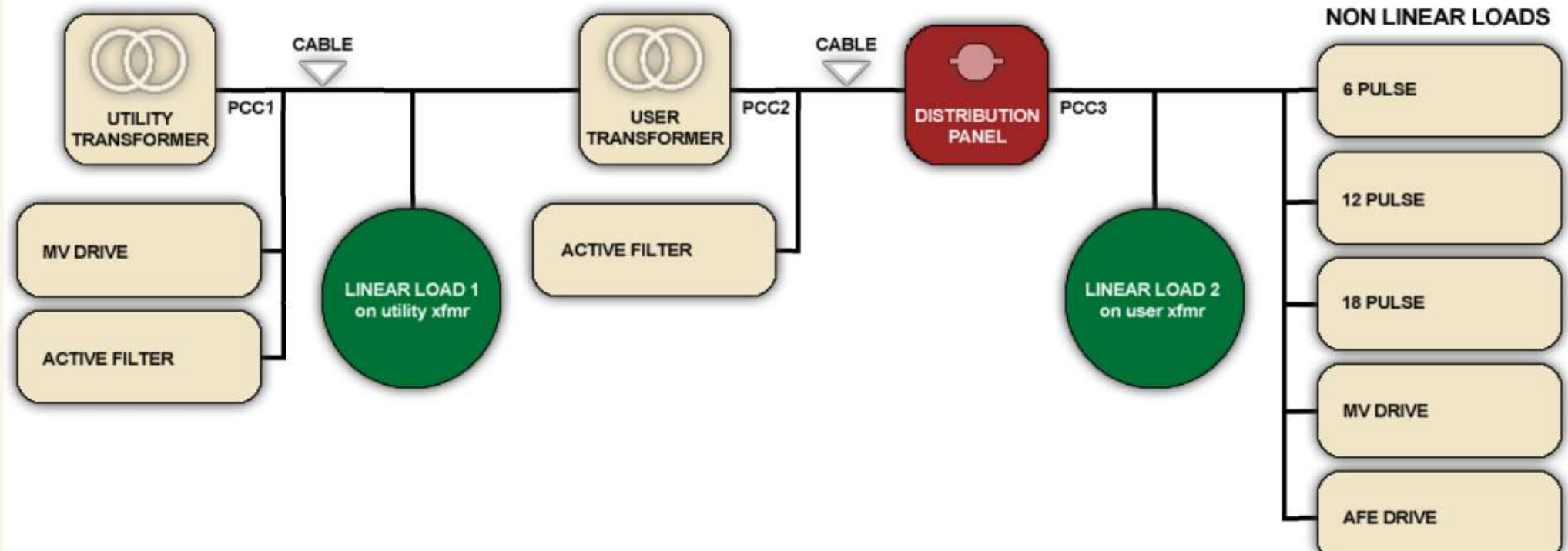
I_{harm} **decreases** as load decreases
(drive is at full speed)

V_{thd} vs Load



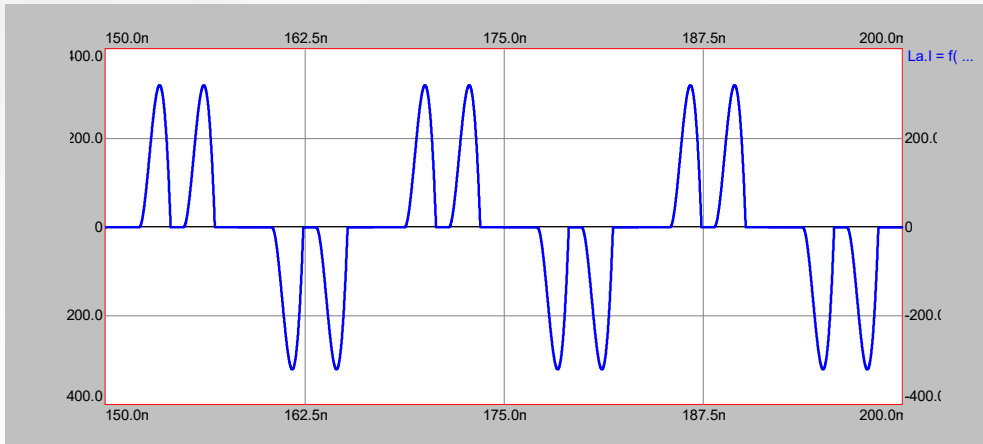
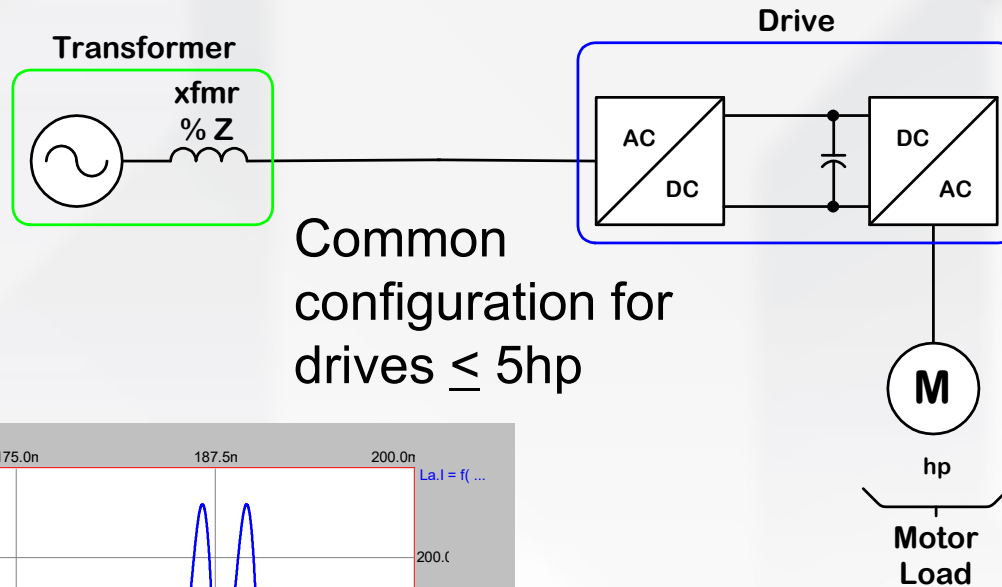
100hp drive on 250kVA xfmr, 6%

Customers who ask about harmonics are also concerned about their effect in their plant



Drive Without DC Link Choke

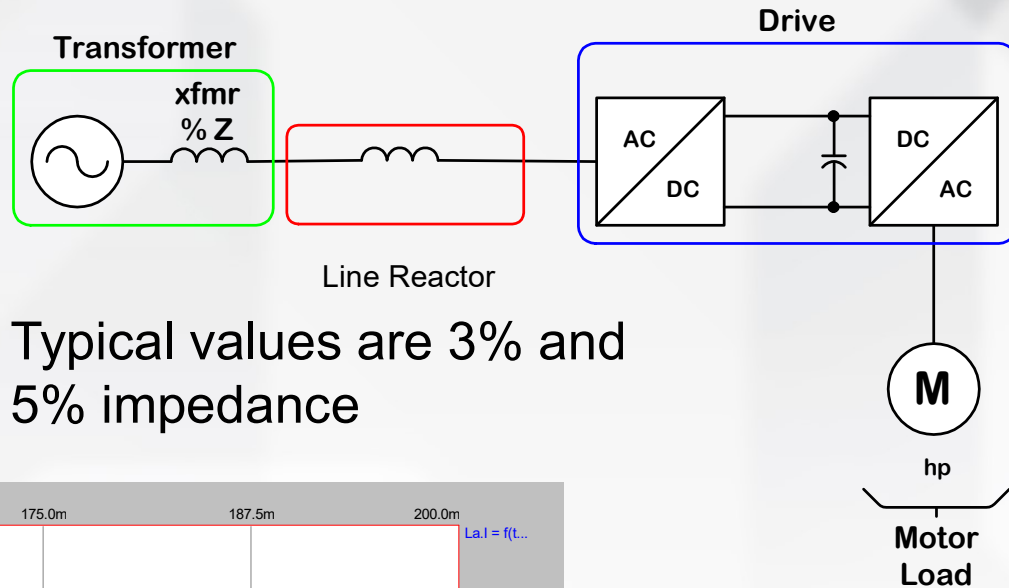
- Typical I_{THD} of 80 to 120%
- Sensitive to line voltage transients
- High peak line currents



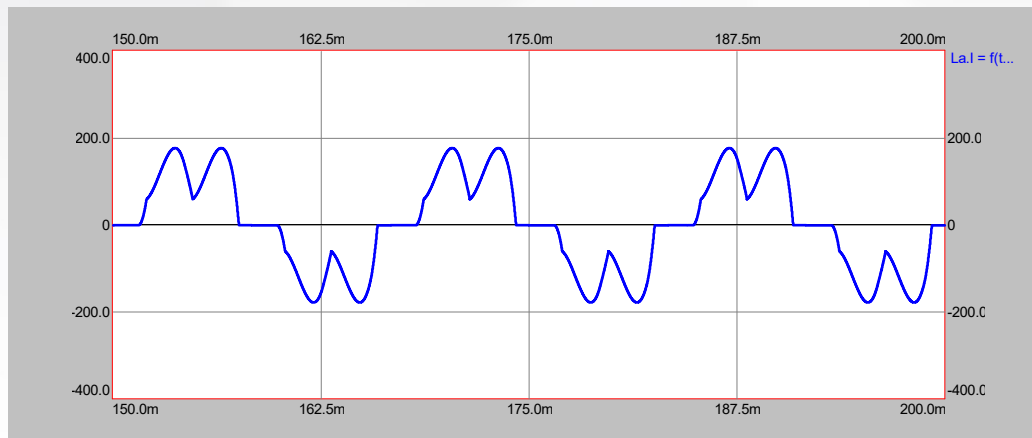
NOTE: I_{pk} about 3x I_{rms}

Line Reactor, Drive w/o DC Link Choke

- Typical I_{THD} of 30 to 45%
- Big help for drives without DC link choke



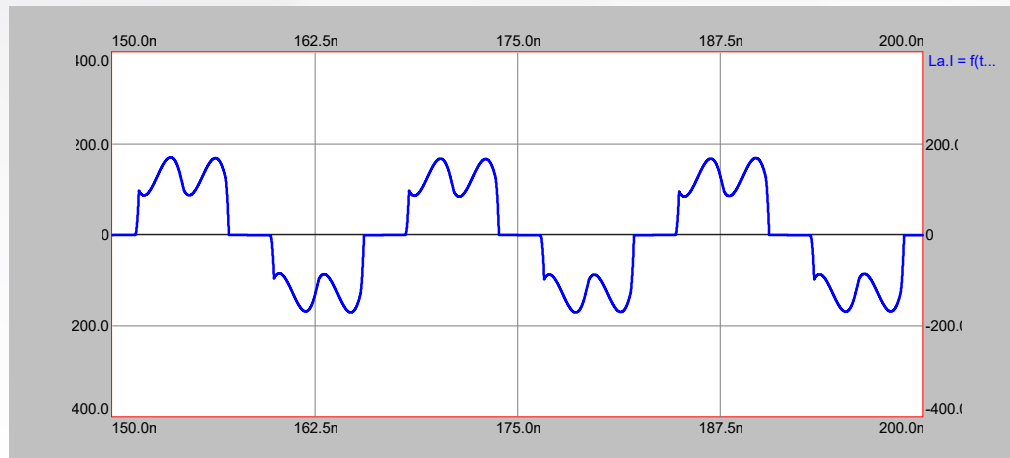
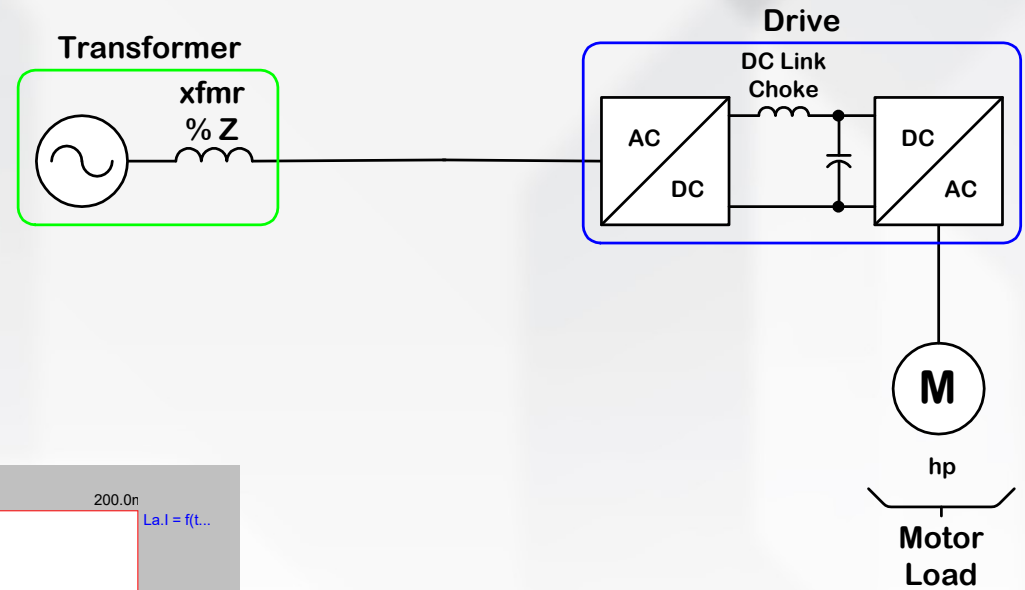
Typical values are 3% and 5% impedance



NOTE: shown is 3% LR

Drive With DC Link Choke

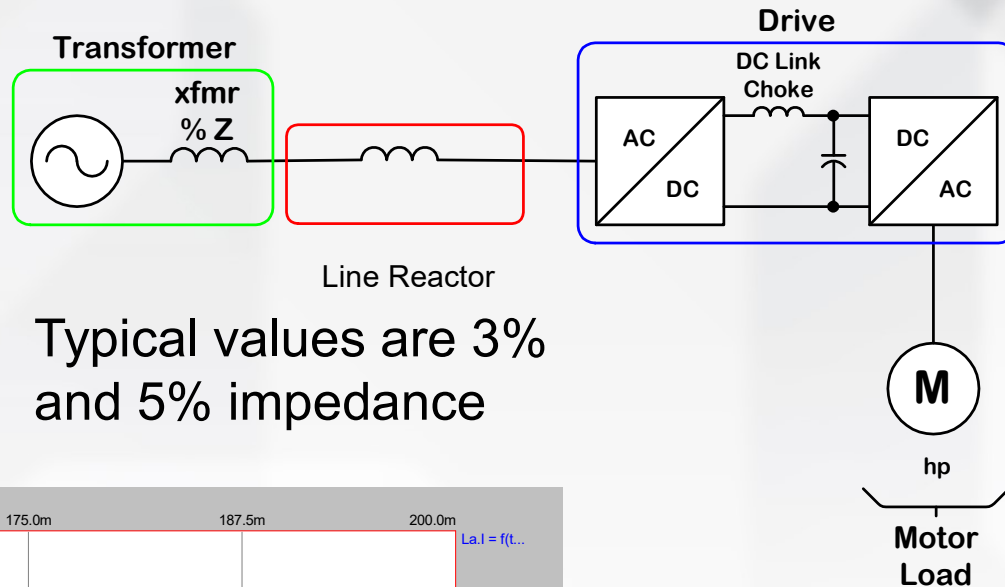
- Typical I_{THD} of 30 to 40%
- Less sensitive to line transients



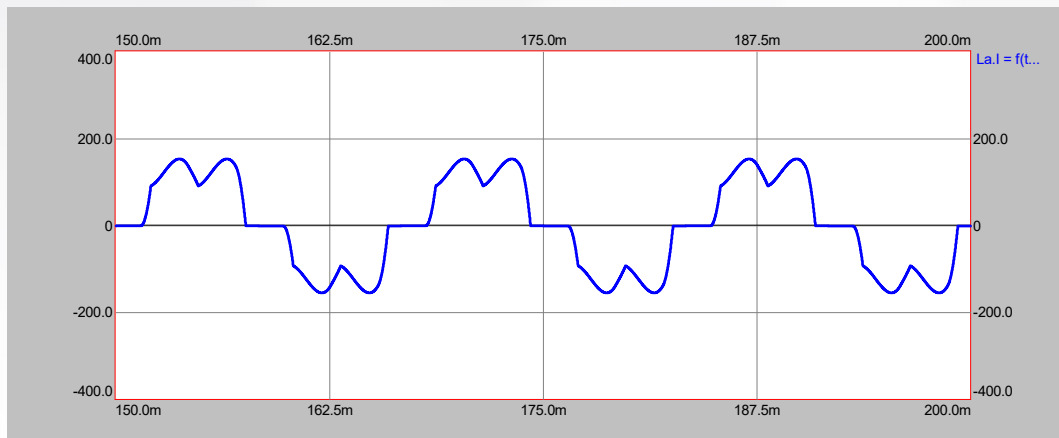
NOTE: I_{pk} about 1.5x I_{rms}

Line Reactor in Addition to a DC Link Choke

- Typical I_{THD} of 20 to 35%
- Big help for drives w/o DC link choke
- 0.75 - 0.95 PF



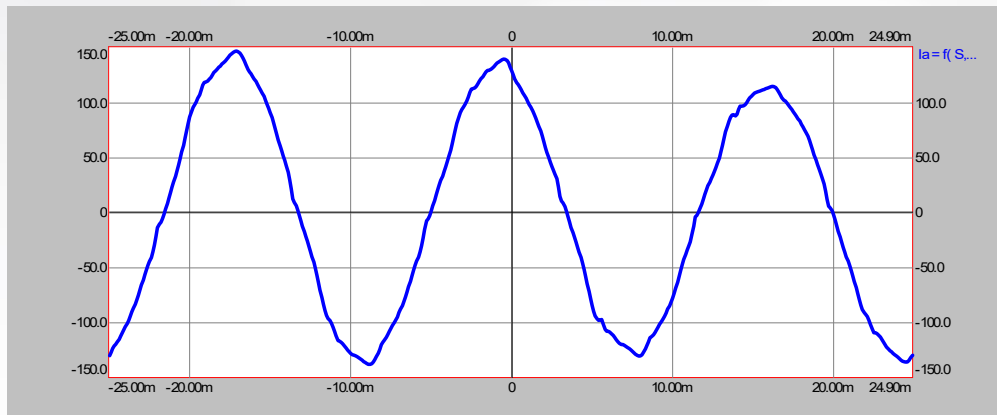
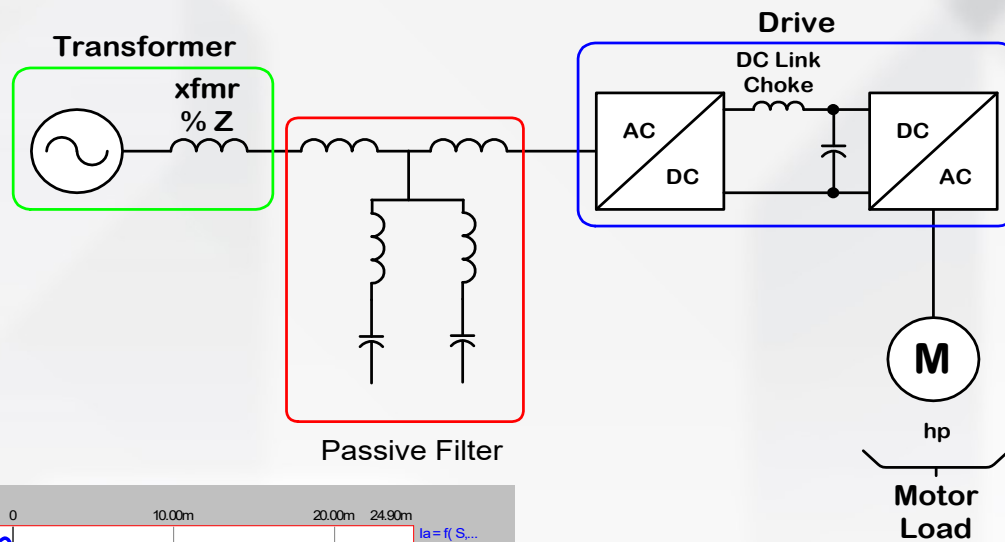
Typical values are 3% and 5% impedance



NOTE: shown is 3% LR

Passive Harmonic Filter

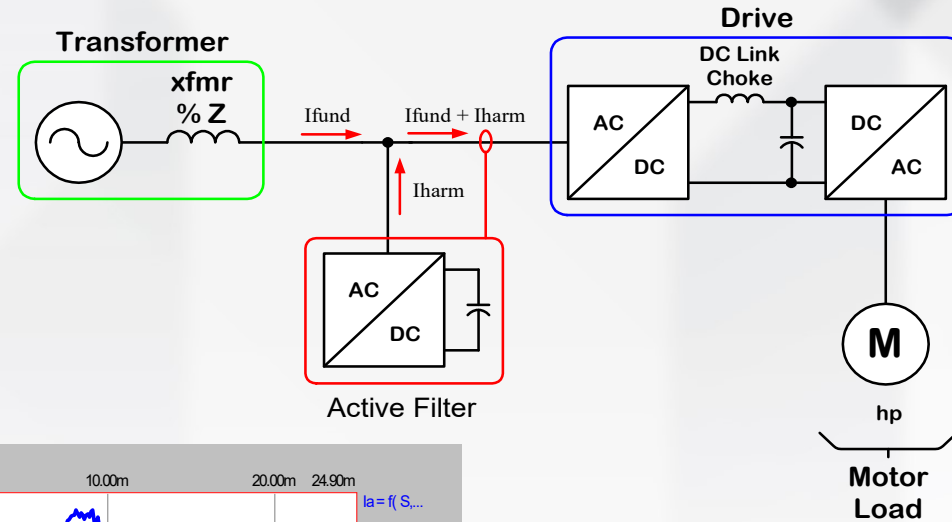
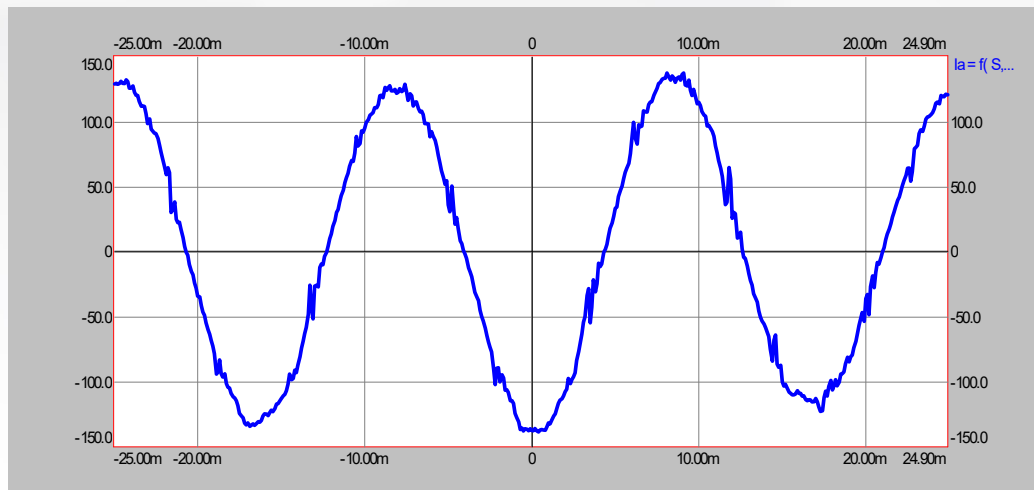
- Typical I_{THD} of 4 to 7%
- 0.3 to 1.0 PF



Active Harmonic Filter

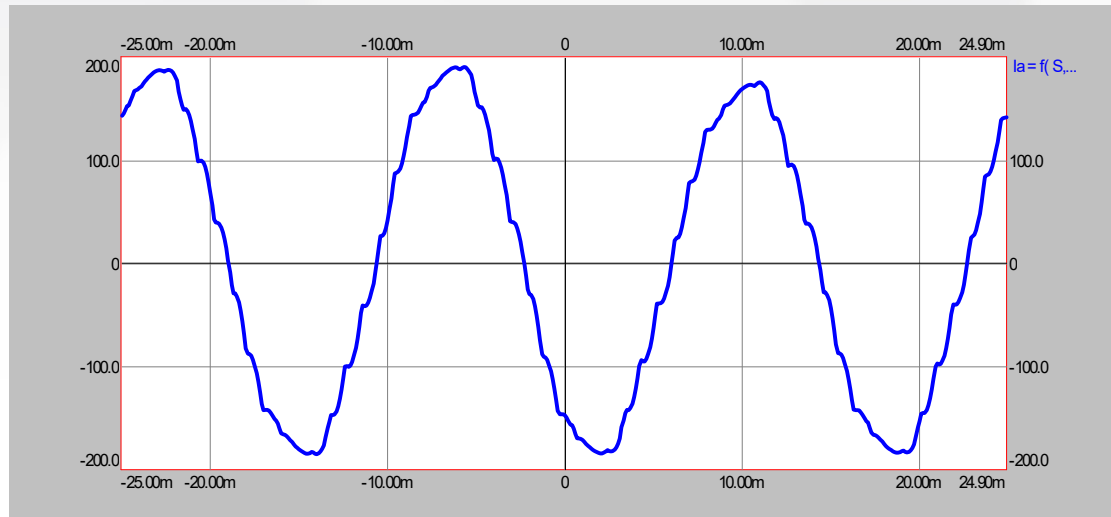
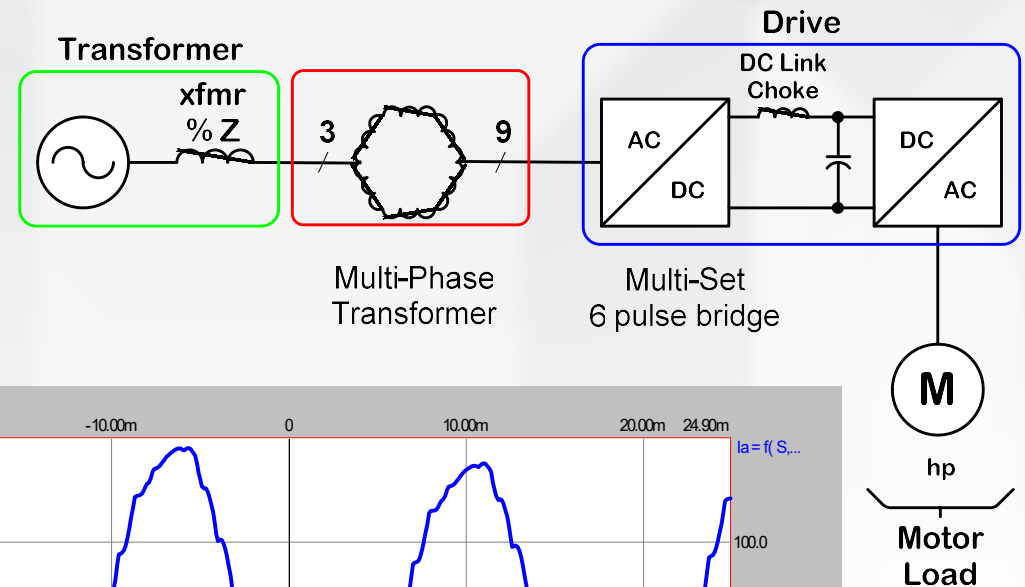
- Typical I_{THD} of 3 to 6%
- 0.9 - 0.99 PF

Current from Transformer



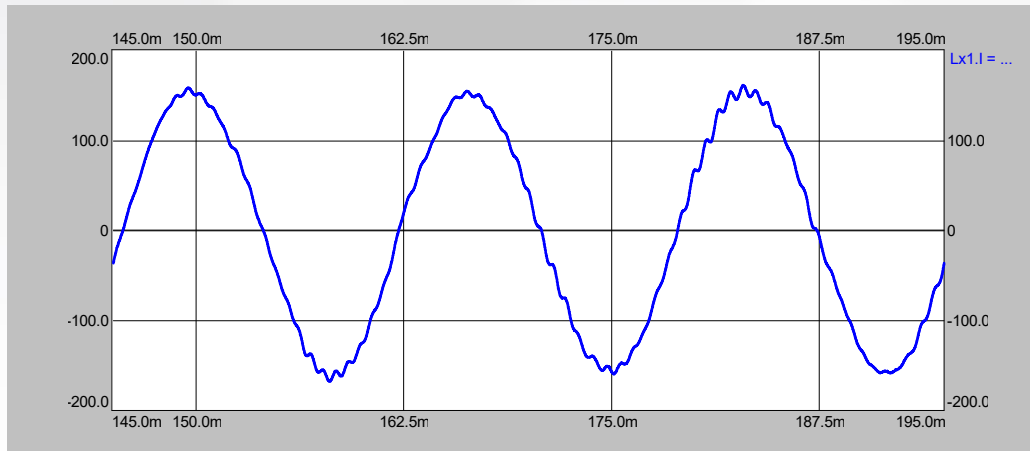
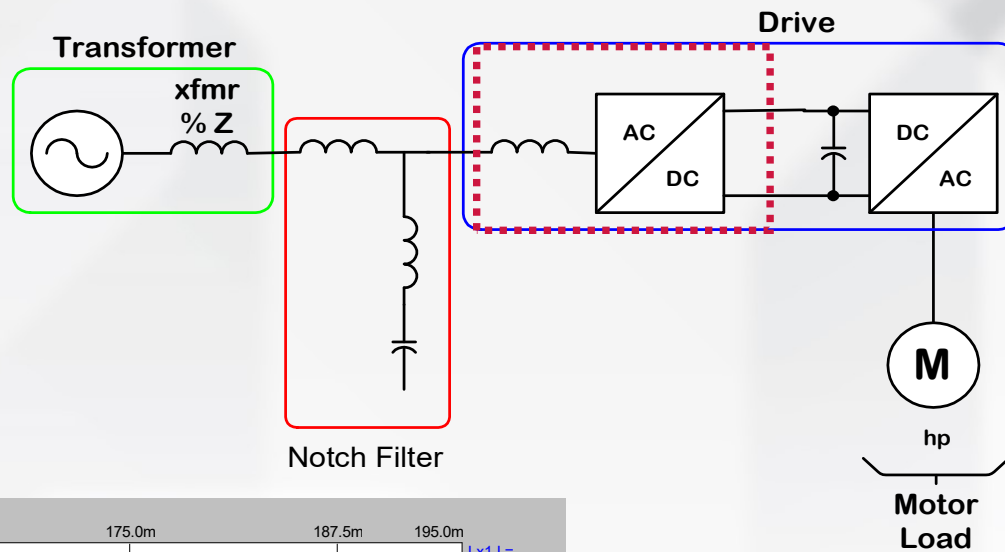
Multi-Pulse

- 12-Pulse Typical I_{THD} of 9 to 12%
- 18-Pulse Typical I_{THD} of 4 to 5%
- 0.90 - 0.99 PF

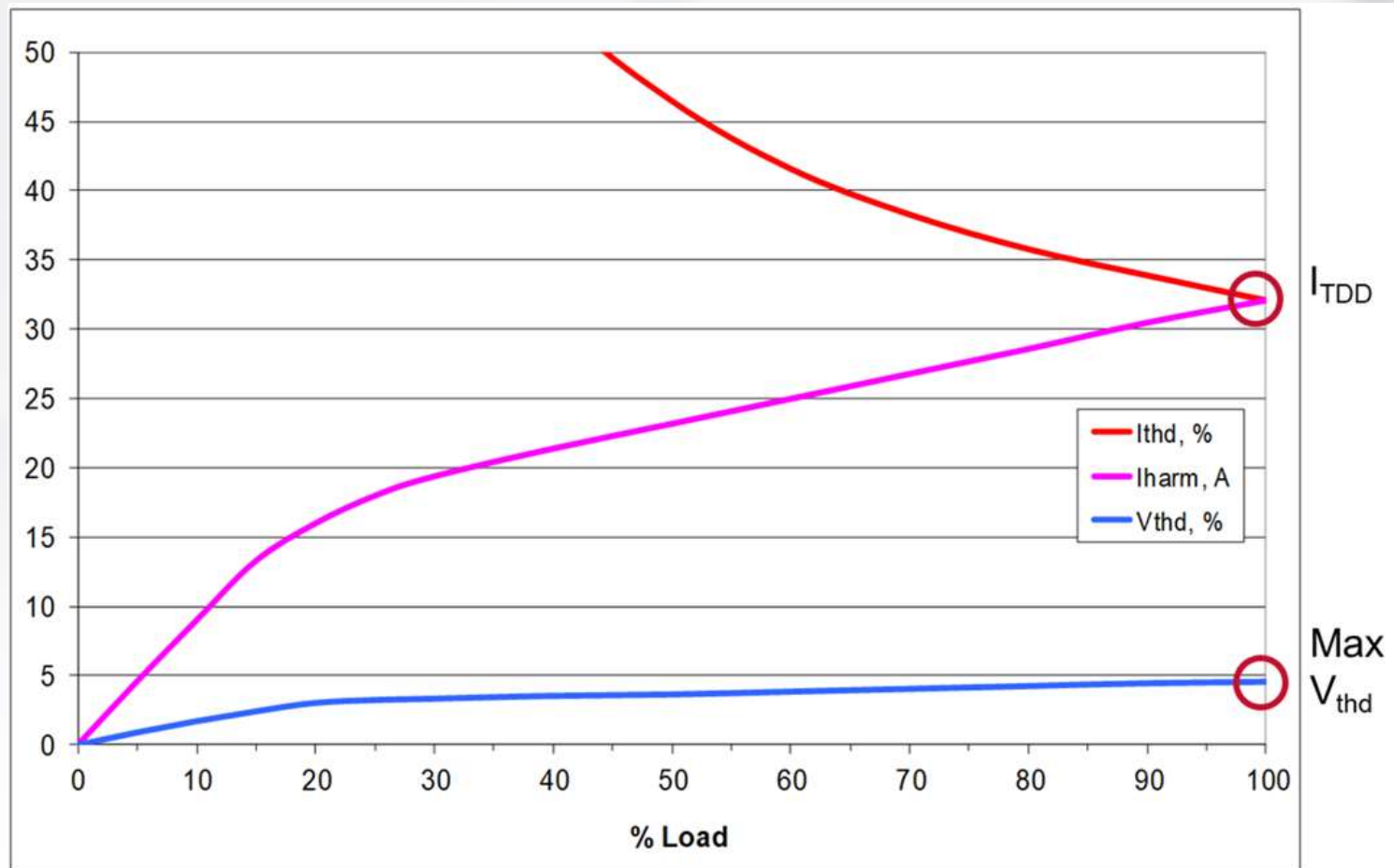


Active Front-End

- Typical I_{THD} of 3 to 5%
- Regen
- 0.8 – 1.0 PF



Important point on Active Front Ends



Harmonic Estimation Tools

Harmonic Estimator Report - One Line

Rockwell Automation

Project Name: Test
End User: XXXX
Customer: RA
Notes: notes

Prepared by: YYY
Date prepared: 12/7/2017
Email of preparer: ZZZ

Version: 170492

Cell Key:
data entry
intermediate calc
harmonic results
Blue Text is a HyperLink

Notes:
PCC is a Point of Common Coupling
A "buffered drive" is one that has a DC Link Choke
A "dfr" is a transformer
All of the values are recalculated when cell data is entered

Please note that the information shown here is typical and does not constitute any guarantee of performance or measurement. Several outside factors can influence the harmonics measured on a power system, including other equipment within the plant and other equipment in neighboring plants. This can include, but is not limited to, drives, varying loads and/or other factory equipment.
The calculated current and voltage harmonics shown in this report are for estimation purposes only.

Source
50 Hz

PCC1
PCC at utility dfr
feet between utility dfr and user dfr: 0

Utility Transformer or Generator
50000 kVA 1
5.00 %Z 1
15000 Vsec 1
0 Isc 1

at PCC1
50000 kVA 1
20320 rated 1
26143 Isc 1
808.3 L, uH 1
1.0 Kfactor
0.0 % Imp total to rated
0.0 % thermal rating
0.0 rms harmonics
0.0 rms fundamental
0.0 rms total

PCC2
PCC at user dfr
feet between user dfr and distribution panel: 0

User Transformer or Generator
500 kVA 2
5.00 %Z 2
450 Vsec 2
0 Isc 2

at PCC2
500 kVA 2
600 rated 2
12028 Isc 2
61.1 L, uH 2
1.0 Kfactor
0.0 % Imp total to rated
0.0 % thermal rating
0.0 rms harmonics
0.0 rms fundamental
0.0 rms total

PCC3
PCC at distribution panel
feet between distribution panel and panel: 0

Distribution Panel
450 Vsec 3
0 Isc 3
0.0 L, uH 3

at PCC3
12028 Isc 3
0.0 L, uH 3

PCC1 Linear Loads
0.00 total hp motor loads
0.00 total kV resistive loads
0.00 additional Amp loads

PCC2 Linear Loads
0.00 total hp motor loads
0.00 total kV resistive loads
0.00 additional Amp loads

PCC3 Linear Loads
0.00 total hp motor loads
0.00 total kV resistive loads
0.00 additional Amp loads

6 pulse unbuf w/o LR
0 feet to panel
0.00 total hp
100.0 % load

6 pulse buf w/o LR
0 feet to panel
0.00 total hp
100.0 % load

6 pulse buf w/ 3% LR
0 feet to panel
0.00 total hp
100.0 % load

6 pulse buf w/ 5% LR
0 feet to panel
0.00 total hp
100.0 % load

6 pulse buf w/ PHF
0 feet to panel
0.00 total hp
100.0 % load

12 pulse buf w/ auto dfr
0 feet to panel
0.00 total hp
100.0 % load

12 pulse buf w/ iso dfr
0 feet to panel
0.00 total hp
100.0 % load

18 pulse buf w/ auto dfr
0 feet to panel
0.00 total hp
100.0 % load

18 pulse buf w/ iso dfr
0 feet to panel
0.00 total hp
100.0 % load

PF75STL/TR Low Harmonic
0 feet to panel
0.00 total hp
100.0 % load

Custom Non-Linear Load
0 Fund at FL
100.0 % load

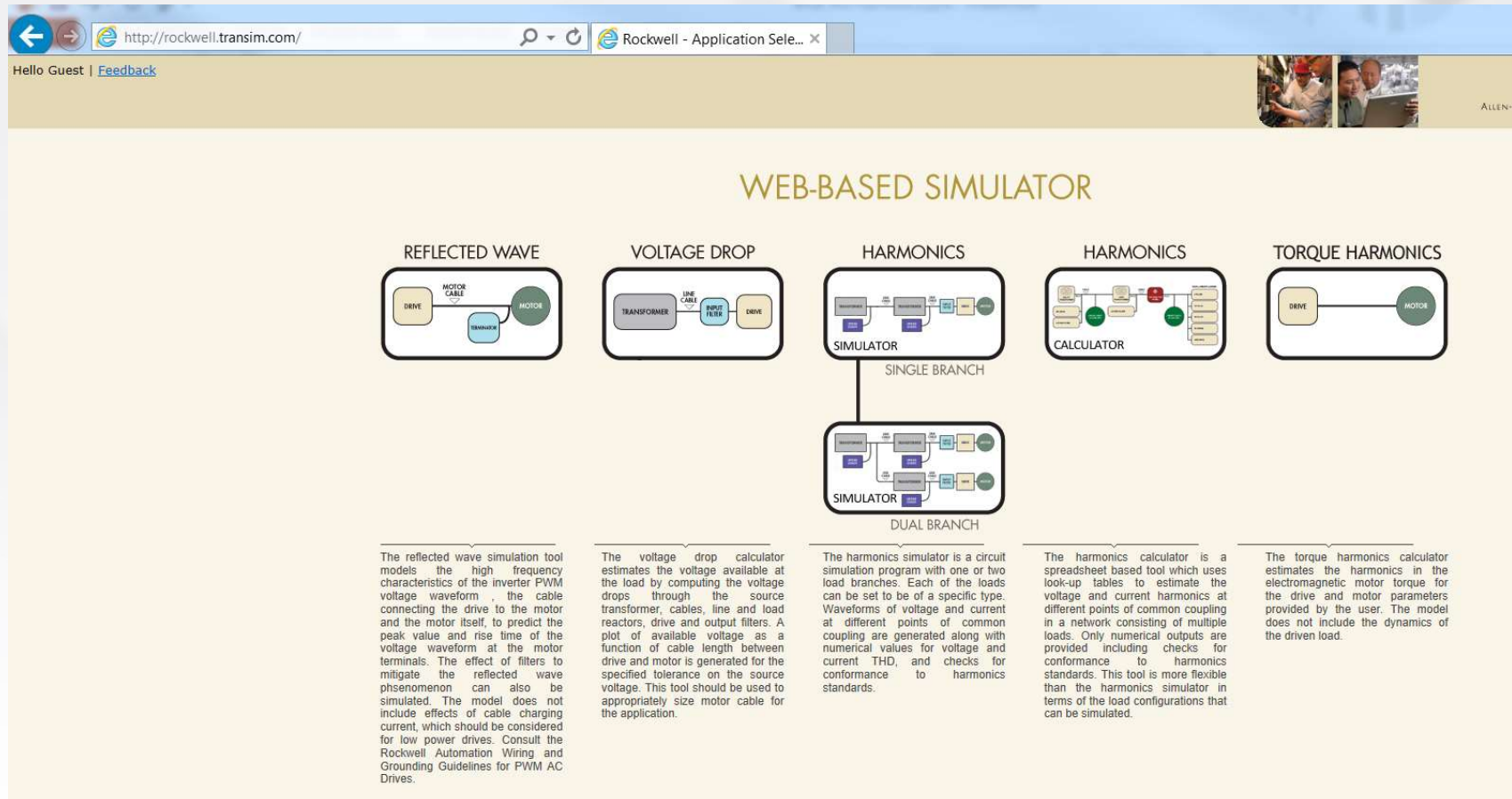
Active Filter on PCC2
5.0 desired % Idd
0 Rated Current
0.0 Required Current

Design Checks: (blank if no issues)
1. Reference
2. Drawings
3. Spec
4. Assumptions
5.
6.
7.

Before using this for the first time, go to the worksheet tab labeled "Tutorial"
For help and additional information, go to the worksheet tab labeled "Notes & Tools"

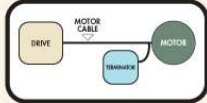
One-Line Report Summary Report Table Report Spectrum VFD Loads Custom Non-Lin Load

Harmonic Estimation Tools - <http://rockwell.transim.com/>



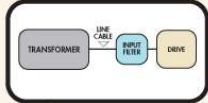
WEB-BASED SIMULATOR

REFLECTED WAVE



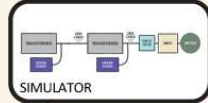
The reflected wave simulation tool models the high frequency characteristics of the inverter PWM voltage waveform the cable connecting the drive to the motor and the motor itself, to predict the peak value and rise time of the voltage waveform at the motor terminals. The effect of filters to mitigate the reflected wave phenomenon can also be simulated. The model does not include effects of cable charging current, which should be considered for low power drives. Consult the Rockwell Automation Wiring and Grounding Guidelines for PWM AC Drives.

VOLTAGE DROP

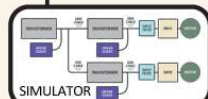


The voltage drop calculator estimates the voltage available at the load by computing the voltage drops through the source transformer, cables, line and load reactors, drive and output filters. A plot of available voltage as a function of cable length between drive and motor is generated for the specified tolerance on the source voltage. This tool should be used to appropriately size motor cable for the application.

HARMONICS



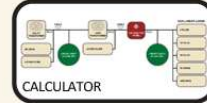
SINGLE BRANCH



DUAL BRANCH

The harmonics simulator is a circuit simulation program with one or two load branches. Each of the loads can be set to be of a specific type. Waveforms of voltage and current at different points of common coupling are generated along with numerical values for voltage and current THD, and checks for conformance to harmonics standards.

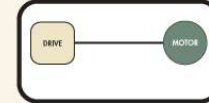
HARMONICS



CALCULATOR

The harmonics calculator is a spreadsheet based tool which uses look-up tables to estimate the voltage and current harmonics at different points of common coupling in a network consisting of multiple loads. Only numerical outputs are provided including checks for conformance to harmonics standards. This tool is more flexible than the harmonics simulator in terms of the load configurations that can be simulated.

TORQUE HARMONICS



The torque harmonics calculator estimates the harmonics in the electromagnetic motor torque for the drive and motor parameters provided by the user. The model does not include the dynamics of the driven load.

Questions?



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