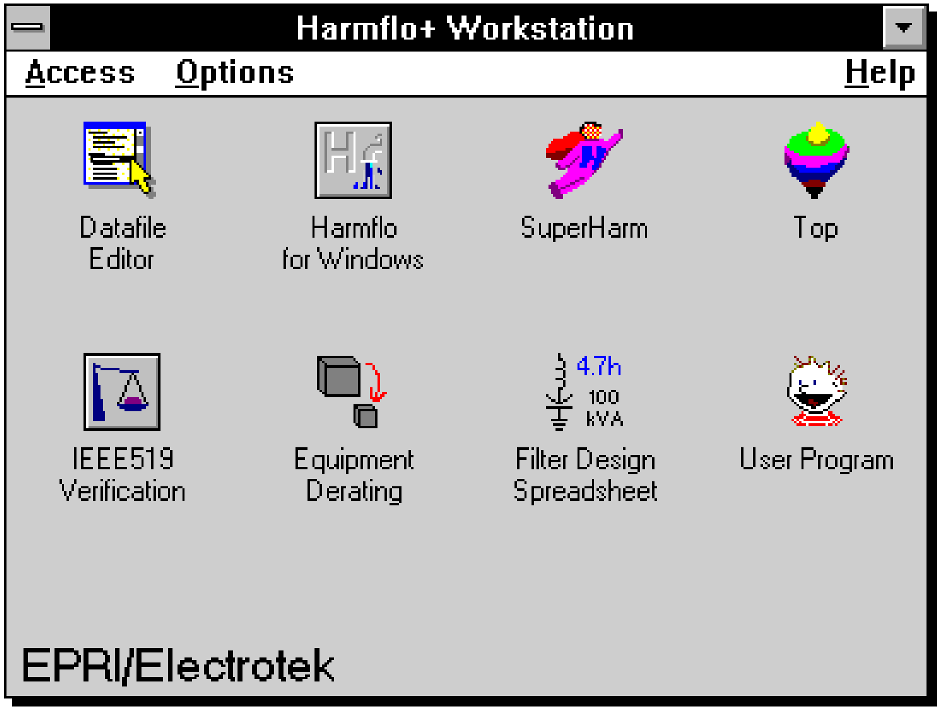
Harmonic Analysis
Using the HarmFlo+ Workstation



HarmFlo+ Case Study Workshop

Modeling and Analysis of Adjustable-Speed Drives

October, 1993

Overview

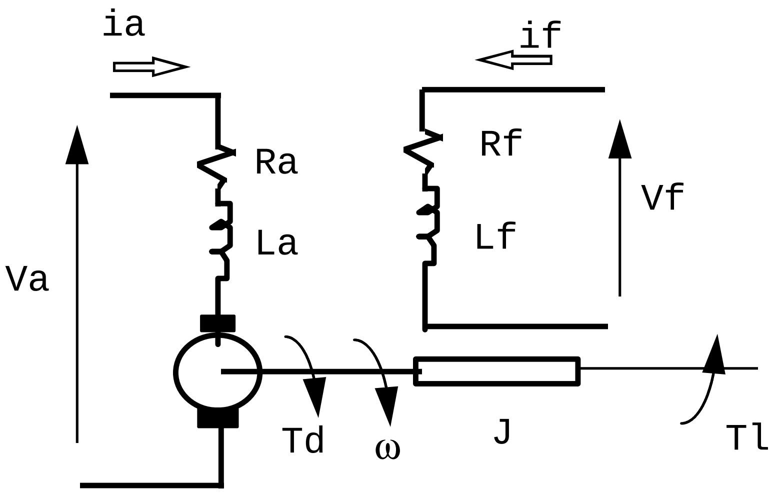
- ❑ Introduction to Power Electronics Modeling
- ❑ Modeling Considerations
- ❑ Development of SuperHarm Models
- ❑ Harmonic Aspects of ASD Applications
- ❑ ASD Case studies

DC Motors

- Advantages:
  - Variable characteristics
  - Extensively used in variable-speed drives
  - A high starting torque
  - A wide range of speed control
  - Simpler and less expensive speed control
- Disadvantages:
  - Needs commutators
  - Costs more
  - Needs more maintenance
  - Not suitable for very high speed applications

DC Motors

- Basic Characteristics of DC Motors



$$V_f = R_f i_f + L_f \frac{di_f}{dt}$$

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + e_g$$

$$e_g = K_v w i_f$$

$$T_d = K_t i_f i_a$$

$$T_d = J \frac{dw}{dt} + B w + T_L$$

Under steady state: $P_d = T_d w$

DC Motors

$$w = \frac{V_a - R_a I_a}{K_v \frac{V_f}{R_f}}$$

for parallel excitation,

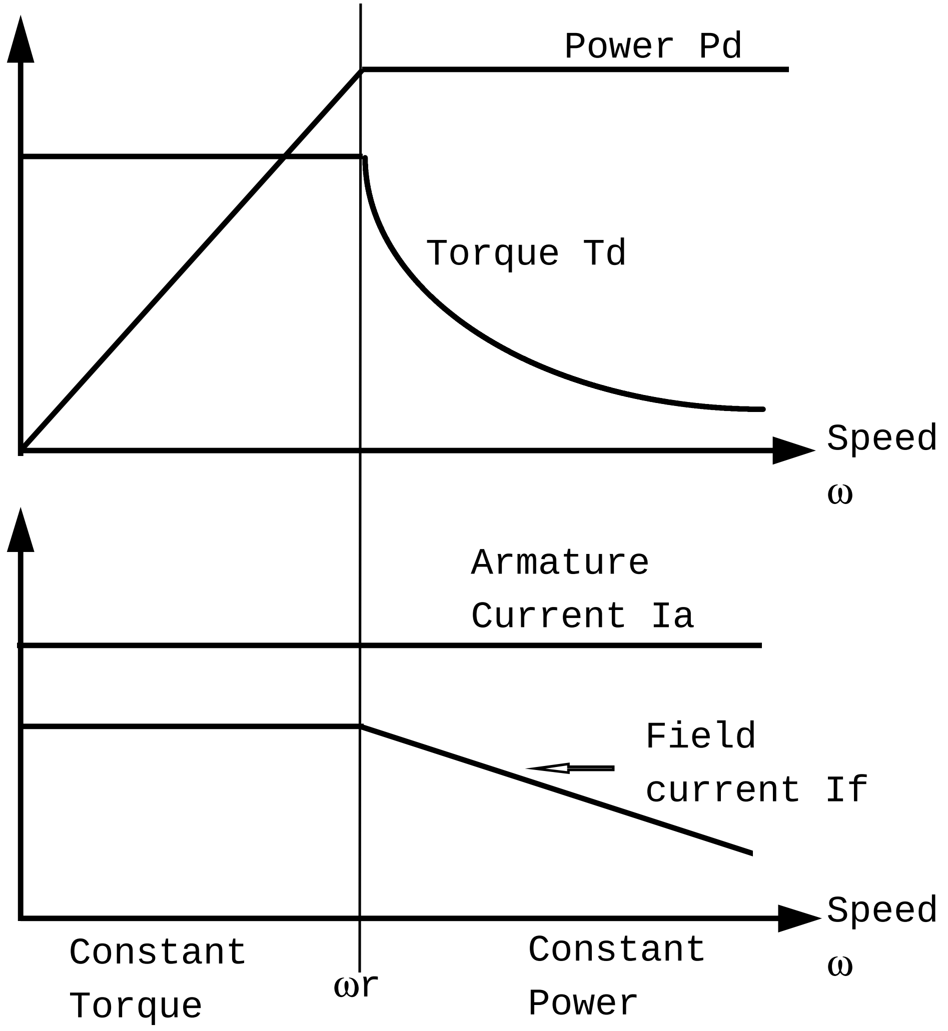
$$w = \frac{V_a - R_a I_a}{K_v I_a}$$

for series excitation

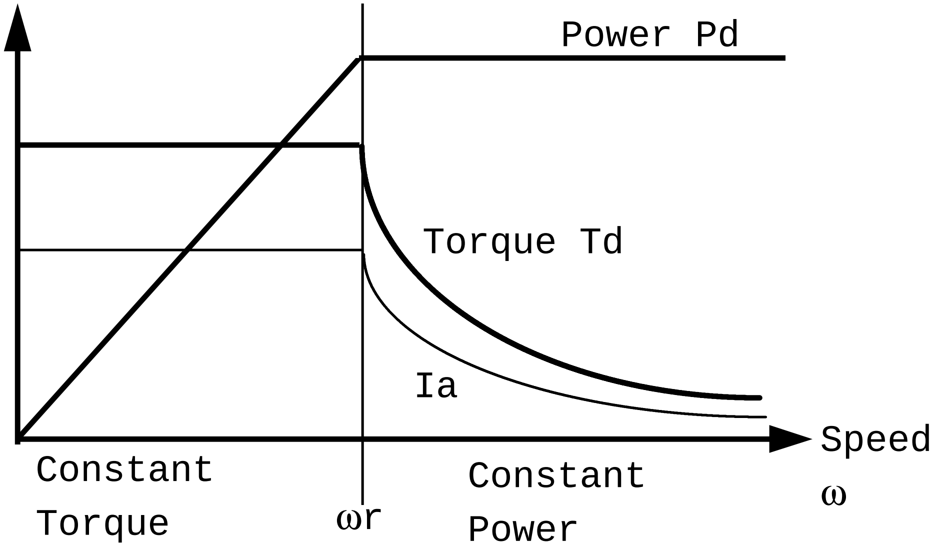
DC Motor speed can be controlled by :

- **Voltage control, controlling V_a,**
- **Field control, controlling I_f, and**
- **Torque demand control, controlling I_a for a fixed I_f**

DC Motors


Power Pd
Torque Td
Speed
ω
Armature
Current Ia
Field
current If
Speed
ω
Constant
Torque
ωr
Constant
Power

DC Motors



For this parallel excited dc motor, in practice, according to the speed range, two control methods are used.

When w<wr, Ia and If are maintained constant w is changed by varying Va for a constant torque.

When w>wr, Va is maintained at the rated value and the If is varied to control the speed for a constant power.

DC Drives

- ❑ Generally, DC drives can be classified into three types:
  - – Single-phase drives
    - » Semiconverter drives
    - » Full-converter drives
  - – Three-phase drives
    - » Semiconverter drives
    - » Full-converter drives
  - – Chopper drives
    - » A dc chopper is connected between a fixed-voltage dc source and dc motor to vary the armature voltage.

AC Motors

- ❑ AC motor advantages
  - – Lightweight (20 to 40 % lighter than dc motor)
  - – Inexpensive
  - – Low maintenance
  - – High speed operation

- ❑ Disadvantages
  - – Expensive drive
  - – Complex control
    - » need sensors, or
    - » vector control

AC Motor Drives

- ☐ AC drives can be
  - Synchronous motor drives
  - Induction motor drives

- ☐ Basic structure
  - AC input-to-DC link-to-AC output

- ☐ Classified by DC link types
  - Voltage source inverter (VSI)
  - Current source inverter (CSI)

AC Motor Drives

- Controls

  Through controlling power converters, inverters, and ac voltage controllers, frequency, voltage/current for variable speed applications can be obtained.

  – Stator voltage control

  – Rotor voltage control

  – Frequency control

  – Stator voltage and frequency control

  – Stator current control

  – Voltage, current, and frequency control

Three-Phase vs. Single-Phase Models

- Single-phase models (positive sequence) for balanced loads, balanced system, balanced harmonic generation
- Separate solution for zero sequence harmonics
- System unbalances, harmonic source unbalances may require a three phase model

When is a Current Source Model Valid?

- Valid for conditions where the system impedance is much smaller than the internal impedance of the harmonic source.

- Not valid when the system approaches resonance (high impedance) ($V_{THD} > 10\%$)

- Some loads look like a voltage source behind a high impedance (arc furnace, fluorescent lightning)

Role of Measurements

- Determine harmonic source characteristics
  - Waveform
  - Spectrum
- Verify harmonic simulation model
  - Use current spectrum from measurement
  - Compare simulated and measured voltage distortion levels
- Statistical Characteristics

Integrating Field Measurements

- ☐ Characterizing Harmonic Sources
  - Correcting phase angles
  - Lumping sources
  - SuperHarm harmonic source models

- ☐ Verifying the system model

Are Phase Angles Necessary?

- ❑ System with only one harmonic source
  - – NO (unless plotting wavefom is desired)

- ❑ System with multiple harmonic sources - may not be necessary if:
  - – Harmonic sources are similar (little cancellation of harmonic currents)

Phase Angle Correction

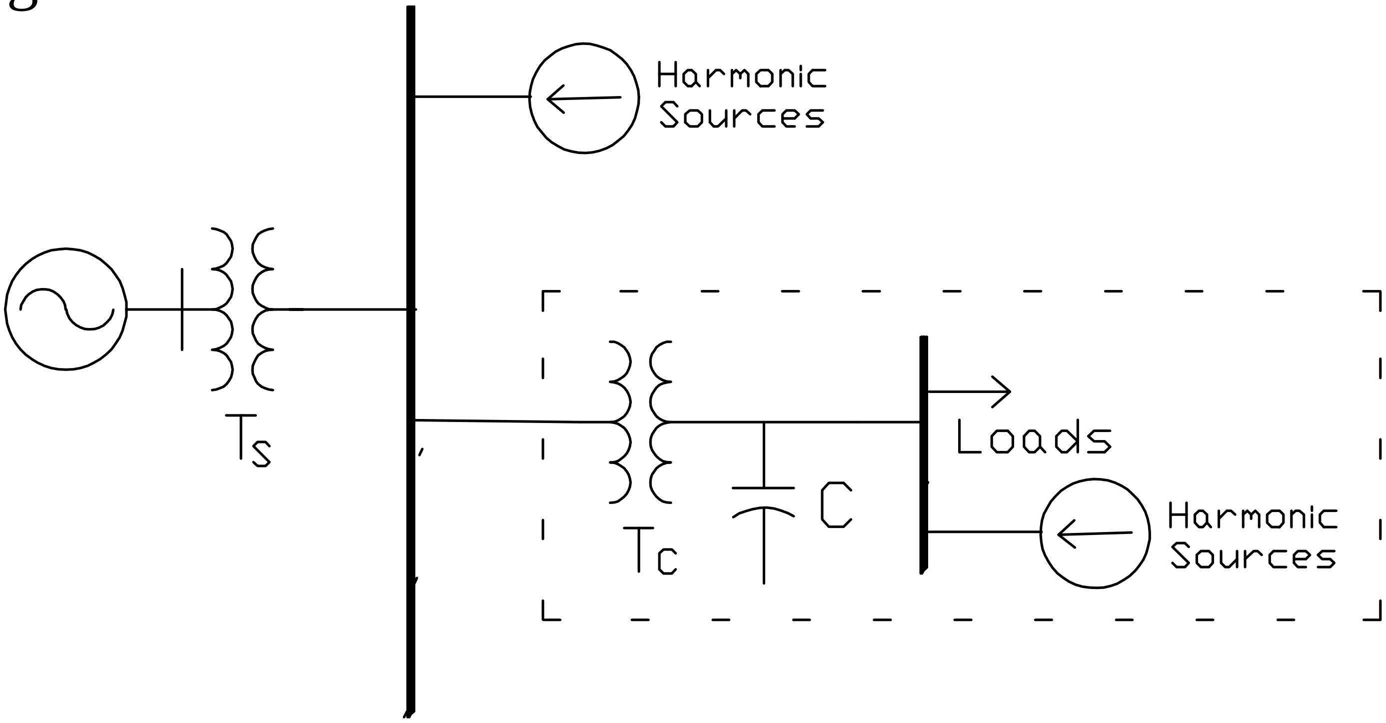
When measured harmonic spectrum is based on a cosine series:

$$\Theta_{h_{\mathrm{sim}}=} = \Theta_{h_{\mathrm{measured}}} + \left(h - 1\right) * 90^\circ$$

Sin series: **SuperHarm, V-HARM, HARMFLO 5.0**
Cos series: **EMTP**

Lumped Harmonic Sources

Can the customer harmonic injection be represented as a single harmonic current source at point of common coupling?



SuperHarm Data Preparation

- ❑ Node Names
- ❑ Tagged Fields, Lists, and Tables
- ❑ Device Library
- ❑ Directives

SuperHarm Data Preparation - cont

Device and Node Names:

Case not important “A” = “a”

_ (underscore) is valid character

Eight (8) characters or less

Convention six (6) characters plus .A, .B, .C

Example: SrcBus.A SrcBus.B SrcBus.C

SuperHarm Data Preparation - cont

Tagged Fields and Lists:

- ☐ Tagged fields entered in any order

Examples: kV = 34.5 MVA = 9.0

- ☐ List: set of items separated by commas

Example: RETAIN CURRENTLIST = {
SourceZ, ASD1, CAP1 }

SuperHarm Data Preparation - cont

Tables:

- ☐ Tables: list of items, where each item is a list

Example:

```
TABLE =       {
              { 1,   100.0,  -75.0},
              { 5,    33.6,  156.0},
              { 7,     1.6, -151.0},
              {11,     8.7, -131.0},
              {13,     1.2,   54.0},
              {17,     4.5,  -57.0},
              {19,     1.3, -226.0},
              {23,     2.7,   17.0},
              {25,     1.2, -149.0}
              }
```

SuperHarm Data Preparation - cont

SuperHarm Device Library:

BRANCH	Single-phase R-X
BRANCH3	Three-phase R-X (sequence quantities)
CAPACITOR	Single or three-phase capacitor
LINEARLOAD	Single-phase load
NONLINEARLOAD	Single-phase current source
SERIESFILTER	Single-phase L-C
TRANSFORMER	Single or three-phase transformer bank
VSOURCE	Single-phase voltage source

SuperHarm Data Preparation - cont

SuperHarm Device: BRANCH

- Example: Branch from BUS1A to BUS2A with $Z = 5\ \Omega$ @ 75°

```
// Single-phase branch, Z = 5 ohms

BRANCH        Name = B1
              From = BUS1A          To = BUS2A
              R = 1.29              X = 4.83
```

SuperHarm Data Preparation - cont

SuperHarm Device: BRANCH3

- ❑ Example: 115kV source equivalent @ bus SRC1?
  $Z_1 = 0.08 + j\ 0.50\ \%$ @ 10 MVA
  $Z_0 = 0.04 + j\ 0.24\ \%$ @ 10 MVA

```
// Three-phase source equivalent

BRANCH3       Name = SRC1
              From.A = V115A      To.A = SRC1A
              From.B = V115B      To.B = SRC1B
              From.C = V115C      To.C = SRC1C
              R1 = 1.10           X1 = 6.63
              R0 = 0.52           X0 = 3.11
```

SuperHarm Data Preparation - cont

SuperHarm Device: CAPACITOR

- Example: 34.5kV, 9.0 MVAr capacitor bank (wye-gnd) @ bus CAP1_A

```
// Three-phase capacitor bank

CAPACITOR    Name = CAP1
             Bus.A = CAP1_A       Bus.B = CAP1_B
             Bus.C = CAP1_C       Neutral = Ground
             kV = 34.5            MVA = 9.0
```

SuperHarm Data Preparation - cont

SuperHarm Device: LINEARLOAD

- Example: 480 Volt, 800 kVA, dpf = 85% served by: 1000kVA Xfmr, 4.16kV /480V, Z_{tx} = 6% @ bus 4160_A

```
// Single-phase linear load, 800 kVA

LINEARLOAD   Name = LinLoad1
             From = 4160_A
             kV = 4160              kVA = 800
             DF = 0.85
             kVAXfmr = 1000
             %R = 0.5               %X = 6.0
```

Note: kV is xfmr high side rating.

SuperHarm Data Preparation - cont

SuperHarm Device: NONLINEARLOAD

- ☐ Example: 480 V, 250 kVA, dc Drive (3-phase rating)

```
// Single-phase nonlinear load, 250 kVA

NONLINEARLOAD       Name = ASD1
                    Bus = 480BUS
                    kV = 0.277   kVA = 83.0   DF = 0.75
           TABLE =  {
                    { 1,   100.0,  -75.0},
                    { 5,    33.6,  156.0},
                    { 7,     1.6, -151.0},
                    {11,     8.7, -131.0},
                    {13,     1.2,   54.0},
                    etc.
                    }
```

SuperHarm Data Preparation - cont

SuperHarm Device: SERIESFILTER

- Example: 480 V, 450 kVAr 4.7th filter bank
  @ bus 4801_A

```
// Single-phase filter bank

SERIESFILTER        Name = Filter1
             CapBus = 4801_A     MidBus = Fil1_A
             IndBus = Ground
             kV = 0.277          kVA = 150
             Harmonic = 4.7
```

SuperHarm Data Preparation - cont

SuperHarm Device: TRANSFORMER

- ❑ Example: 1500 kVA, 13.8kV / 480 V transformer, Z_{tx} = 6%

```
// Single-phase transformer

TRANSFORMER  Name = StepTran     MVAB.HX = 0.500
             X.1 = 480BUS        X.2 = GROUND
             H.1 = SERVENT       H.2 = GROUND
             %X.HX = 6.0         KV.X = 0.277
             KV.H = 7.967
```

SuperHarm Data Preparation - cont

SuperHarm Device: VSOURCE

- ❑ Example: 18.8kV Source @ bus SRC1_A

```
// Single-phase voltage source

VSOURCE      Name = UTILSRC
             Bus = SRC1_A       Freq = 60.0
             Mag = 7967         Ang = 0.0
```

SuperHarm Data Preparation - cont

Block and Line Comments:

//	Comment line (anywhere on line)
!	Comment line (must be in column 1)
/* - */	Block comment (every thing in between)

SuperHarm Data Preparation - cont

#DEFINE and #UNDEF:

- ☐ #DEFINE Identifier Text_String

  Example: #DEFINE 480LNV = 277.1281

  Mag = 480LNV

- ☐ #UNDEF Identifier

SuperHarm Data Preparation - cont

DISCARD and RETAIN:

- ❑ DISCARD

  Currents = Yes | No
  CURRENTLIST = { Asd1, Drive1, Arc1 }

- ❑ RETAIN

  Voltages = Yes | No
  VOLTAGELIST = { Bus1, Bus2 }

SuperHarm Data Preparation - cont

#INCLUDE:

- #INCLUDE “FileSpec”

- #INCLUDE “FileSpec” (Param_1, Param_2,...)

  %n - replacement parameters

SuperHarm Data Preparation - cont

Inline Math:

- ❑ Mathematical expression: @”expression”
- ❑ RPN Notation

Example:

$$\frac{480}{\sqrt{3}} \quad = 480\ 3\ \mathrm{SQRT}\ /$$

SuperHarm Data Preparation - cont

SCAN:

- SCAN directive applies one or more constant current sources to the system

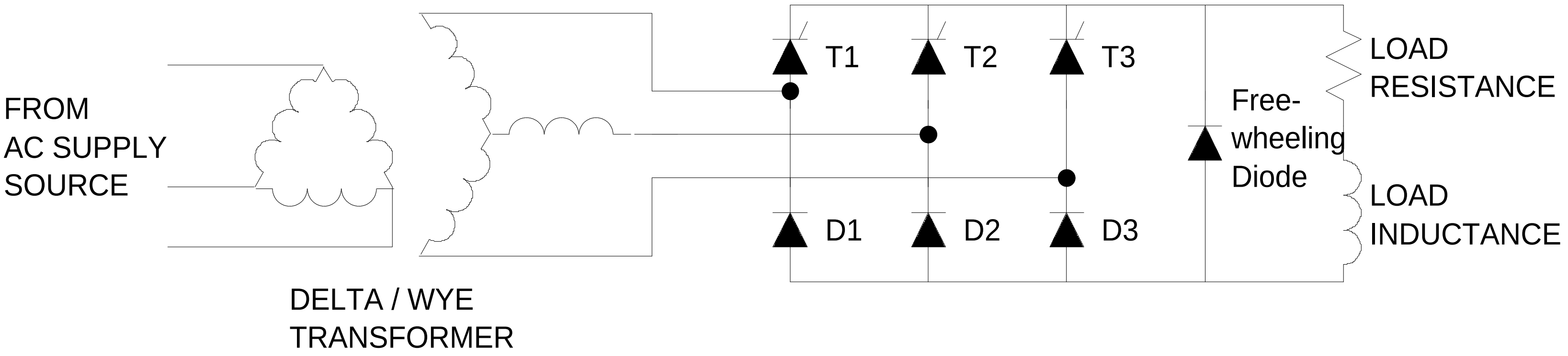
```
// Frequency Scan Request

SCAN             Name = Scan1
             Bus = 480_A  Ang = 0
             FMin = 60.0  FInc = 10    FMax = 1500
```

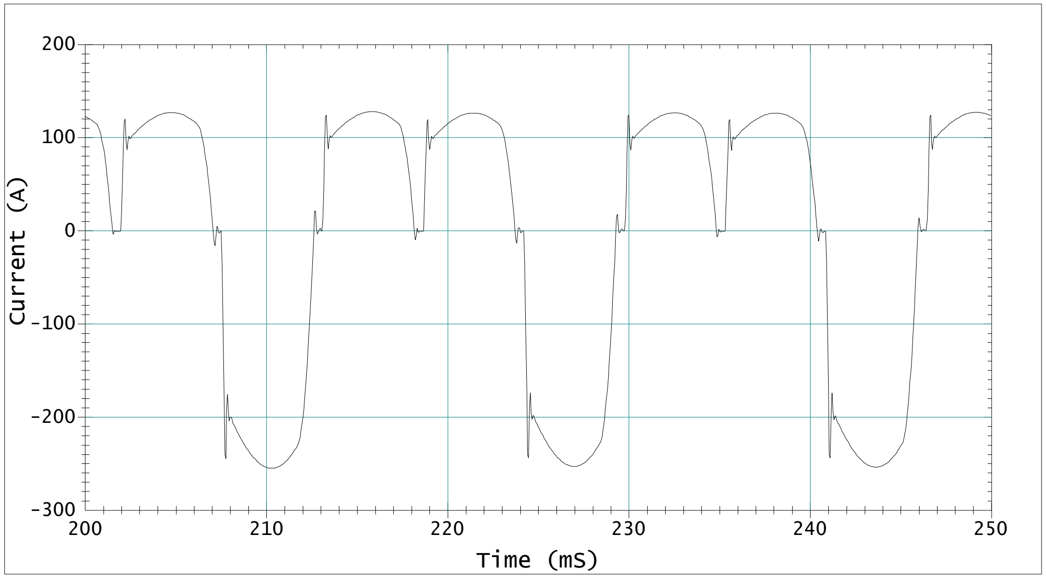
Converter Harmonic Characteristics

- Characteristic harmonics for different types of drives are different.
- Contents of the harmonic spectrum change with the operation condition.
- For a continuous current mode operation, to predict the harmonic generated by the drive - assume the ac line current with square wave waveshape can generate acceptable results.
- Even with a balanced ac supply, the operation of a semiconverter can generate even harmonics.

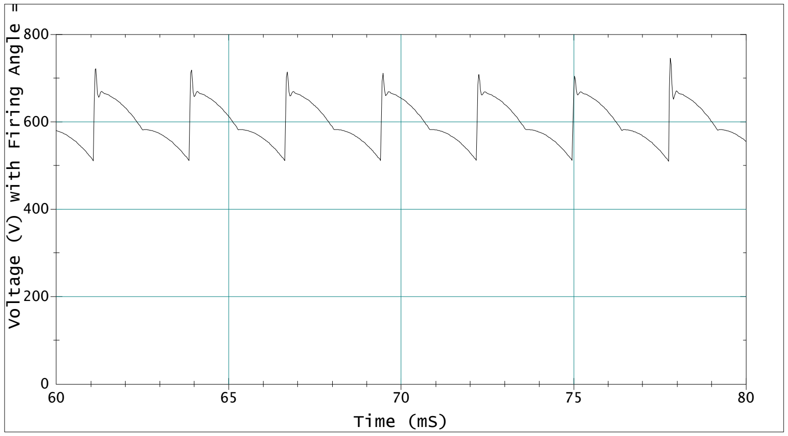
Three-Phase Semiconverter

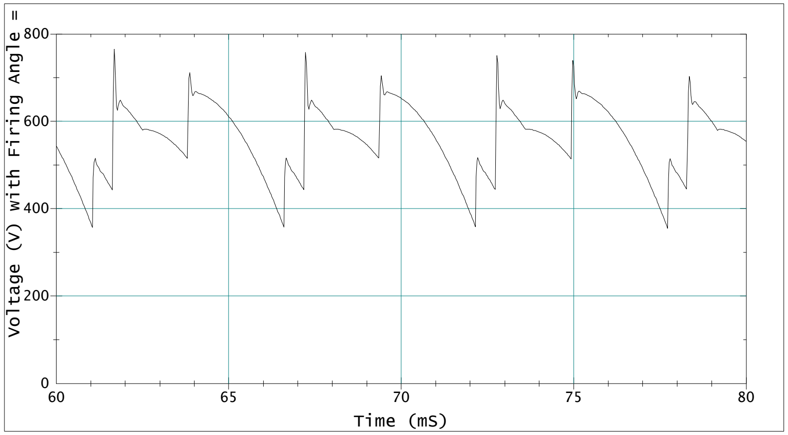


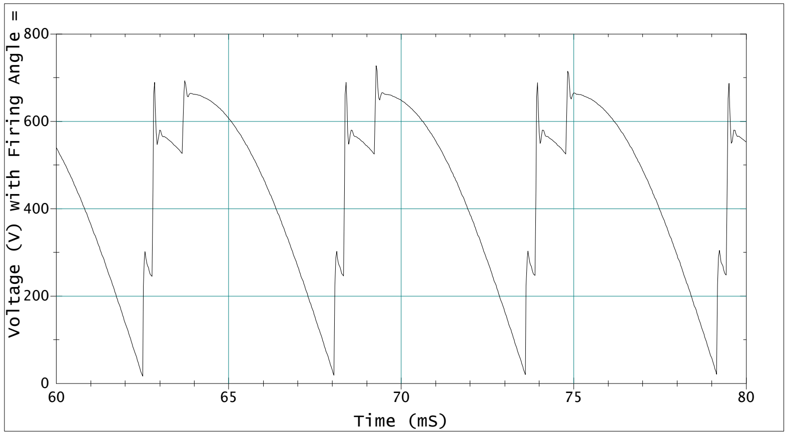
Three-Phase Semiconverter - cont



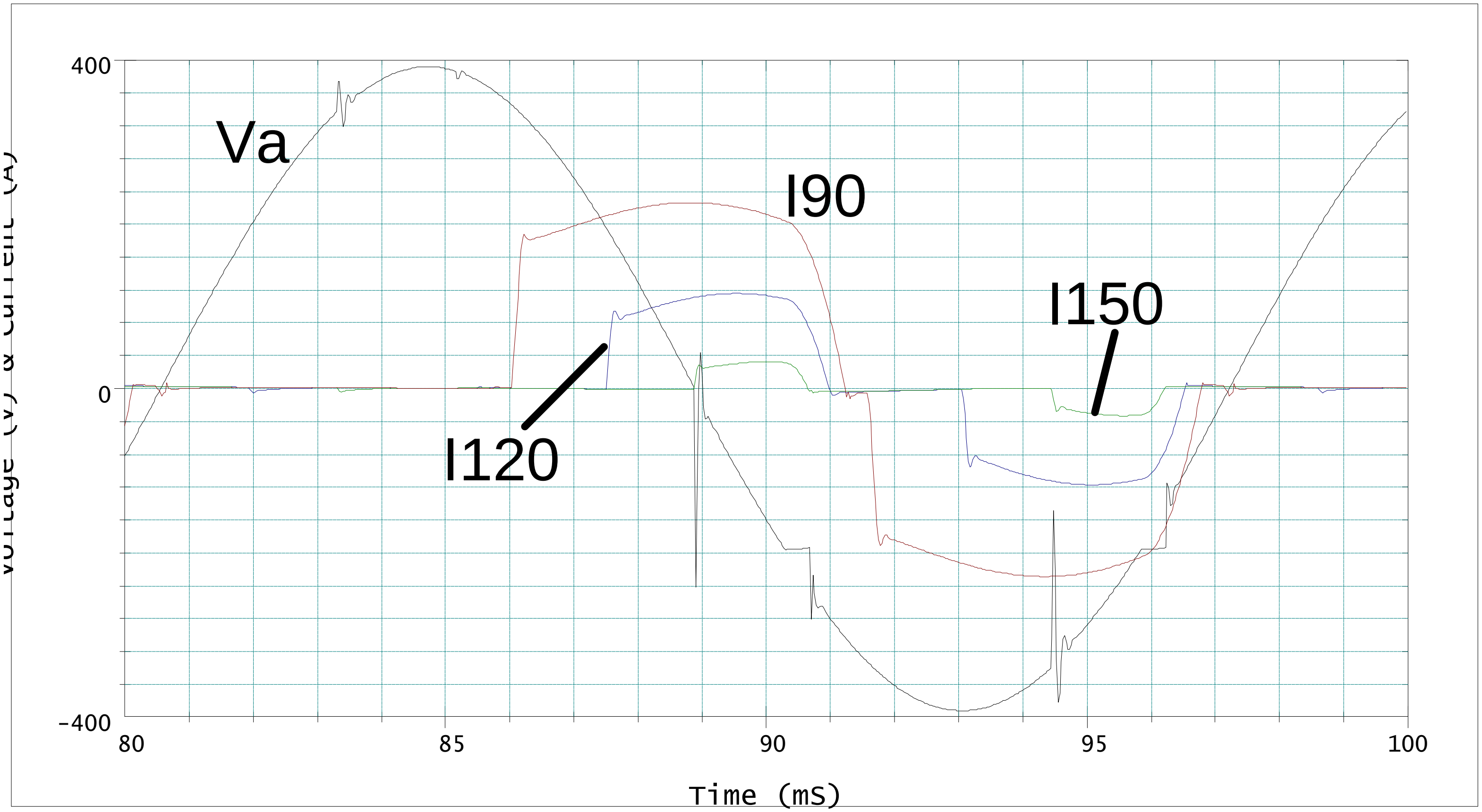
Three-Phase Semiconverter - cont







Three-Phase Semiconverter - cont



Three-Phase Semiconverter - cont

$$a_{n=2m} = \frac{2I_{dc}}{np}\sin(n\frac{p}{6})(1-\cos na)$$

$$b_{n=2m} = \frac{-2I_{dc}}{np}\sin(n\frac{p}{6})\sin(na)$$

`for n=2m, m=1,2,3, ....`

$$a_{n=2m+1} = \frac{-2I_{dc}}{np}\cos(n\frac{p}{6})\sin(na)$$

$$b_{n=2m+1} = \frac{2I_{dc}}{np}\cos(n\frac{p}{6})[1+\cos(na)]$$

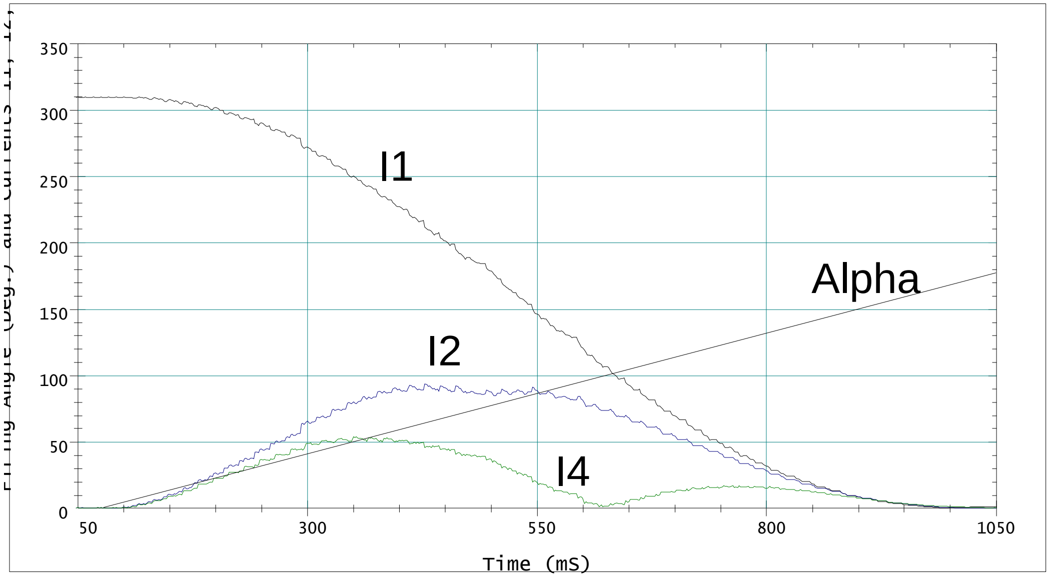
`for n=2m+1, m=0, 1, 2, 3, ...`

Three-Phase Semiconverter - cont

$$\left|C_{n=2m}\right| = \sqrt{a_n^2 + b_n^2}$$

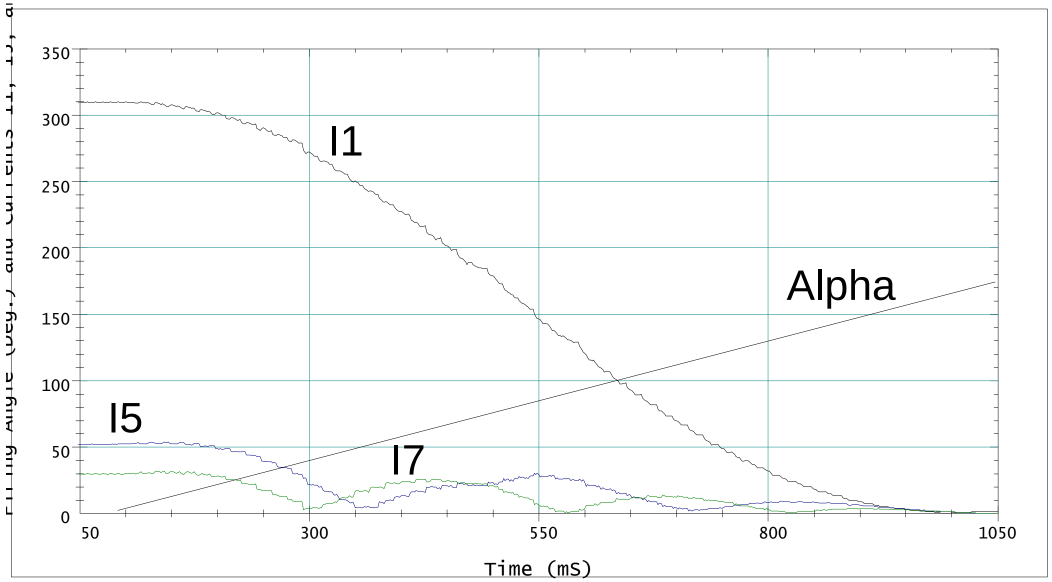
$$= \frac{2\sqrt{2}I_{dc}}{np}\sin(n\frac{p}{6})\sqrt{1-\cos(na)}$$

m=1,2,3,....



Fundamental and Even Harmonics

Three-Phase Semiconverter - cont



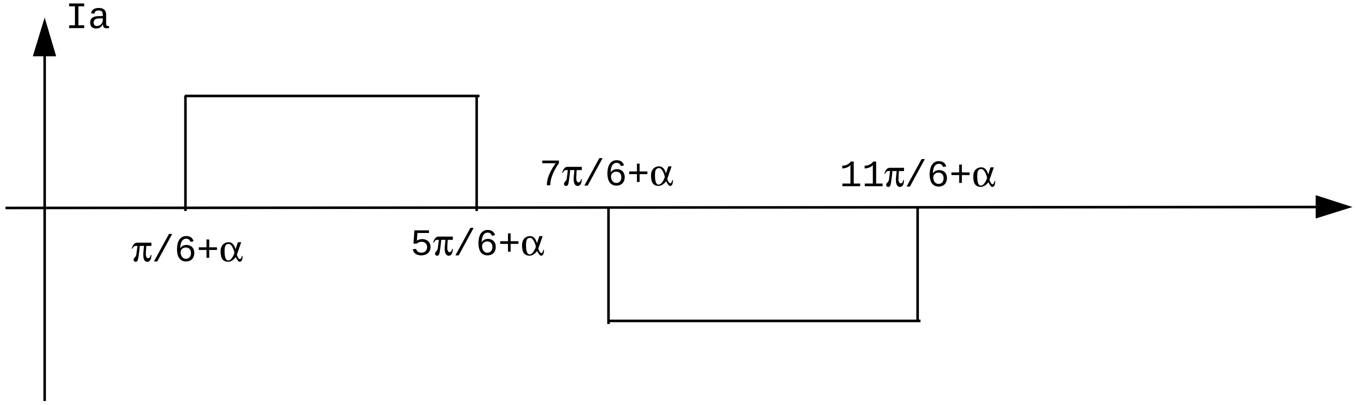
Fundamental and Odd Harmonics

Three-Phase Full-Converter

Average DC output voltage
for three-phase full converter
under idealized condition.

$$
\begin{aligned}
V_{dc} &= \frac{3\sqrt{3}V_{\lg-peak}}{p} Cos\,a \\
&= \frac{3\sqrt{2}V_{ll-rms}}{p} Cos\,a \\
&= 1.35 V_{ll-rms} Cos\,a
\end{aligned}
$$

Idealized line current waveform for three-phase
full converter.



Three-Phase Full-Converter - cont

`Characteristic current harmonics for three-phase full converter under idealized condition`

$$i_a(t) = \sum_{n=1,3,5,...}^{\infty} (a_n \cos nwt + b_n \sin nwt)$$

$$a_n = \frac{1}{p} \int_0^{2p} i_a(t) \cos nwt d(wt) \qquad b_n = \frac{1}{p} \int_0^{2p} i_a(t) \sin nwt d(wt)$$

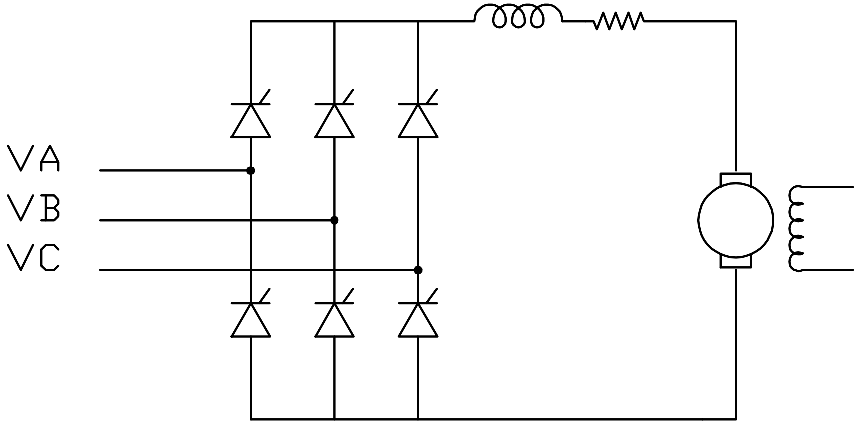
$$= -\frac{4I_a}{np} \sin \frac{np}{3} \sin na \qquad = \frac{4I_a}{np} \sin \frac{np}{3} \cos na$$

`or`

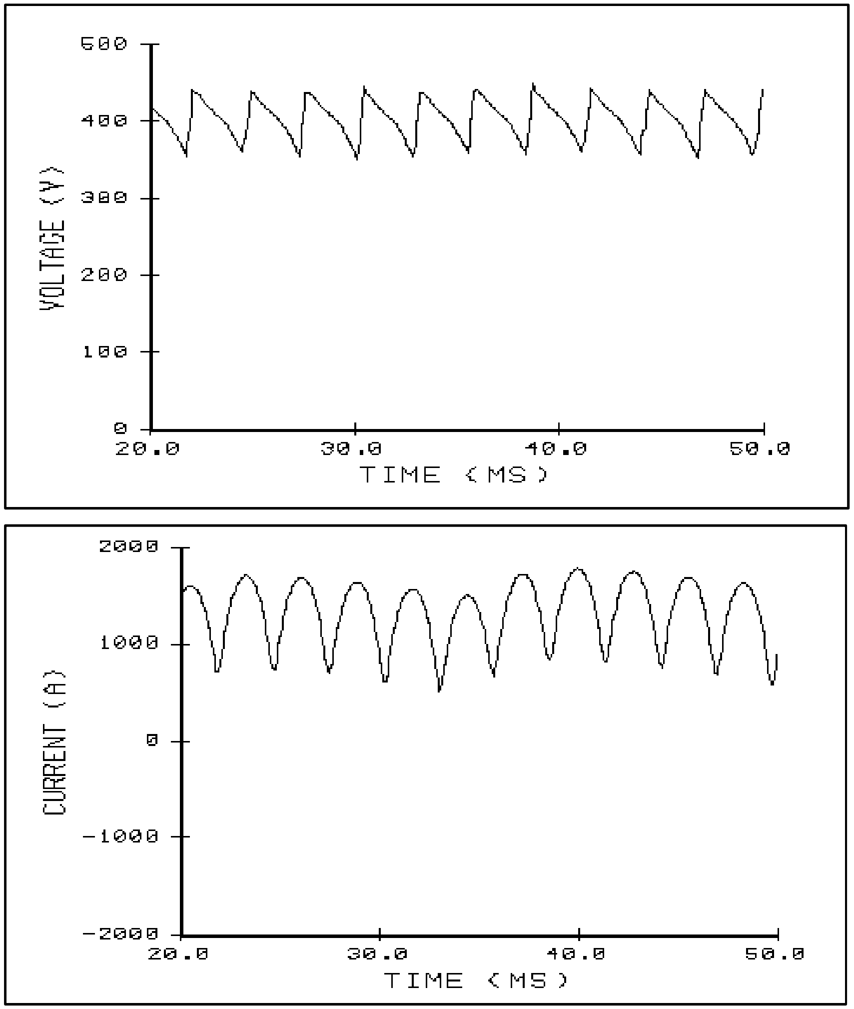
$$i_a(t) = \sum_{n=1,3,5,...}^{\infty} \sqrt{2} I_n \sin(nwt + f_n)$$

$$I_n = \frac{\sqrt{(a_n^2 + b_n^2)}}{\sqrt{2}} = \frac{2\sqrt{2} I_a}{np} \sin \frac{np}{3} \qquad f_n = \tan^{-1} \frac{a_n}{b_n} = -na$$

ASD Types - dc Motor Drive



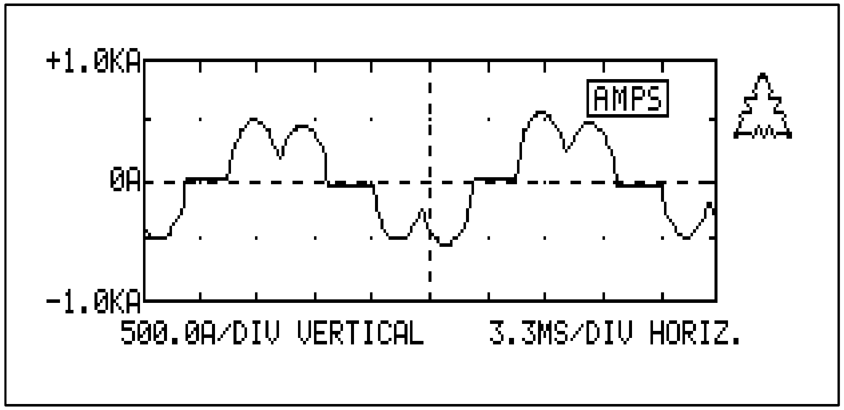
Motor Voltage & Current



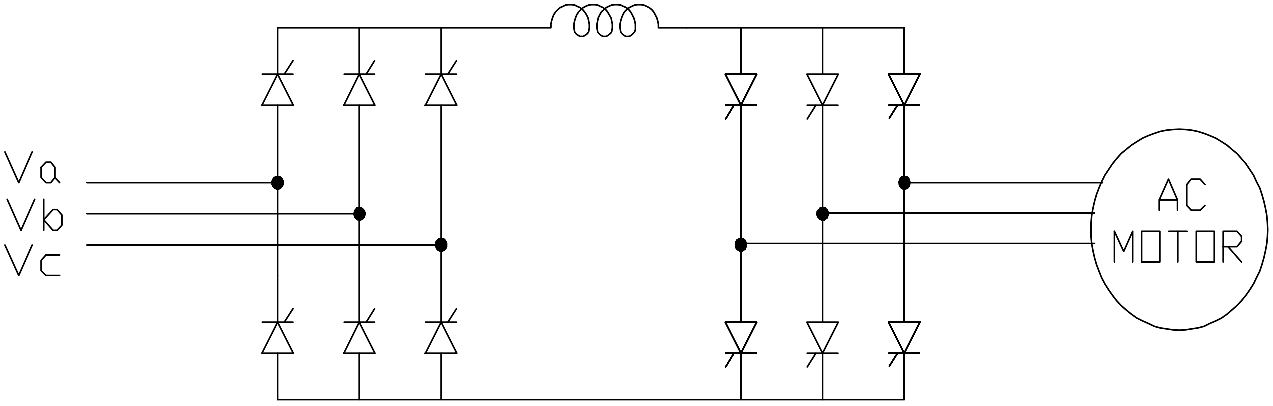
Characteristics and Applications:

- ❑ dc drives provide excellent control of both speed and torque
- ❑ Sizes range into 1000's of HP
- ❑ dc motor drive systems can have significant reactive power requirements.

dc Motor Drive - Snapshot #1



ASD Types - Current Source Inverter

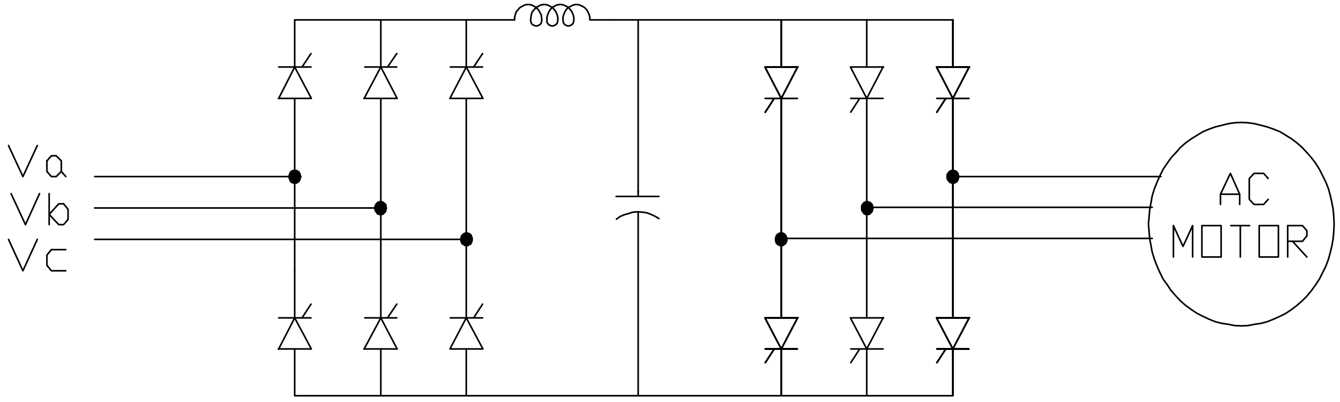


Characteristics and Applications:

- dc inductance maintains constant dc current for inverter
- CSI drives used for very large motors and high-intertia loads
- Power factor may be poor due to phase control of rectifier

Motor Voltage & Current

ASD Types - Voltage Source Inverter

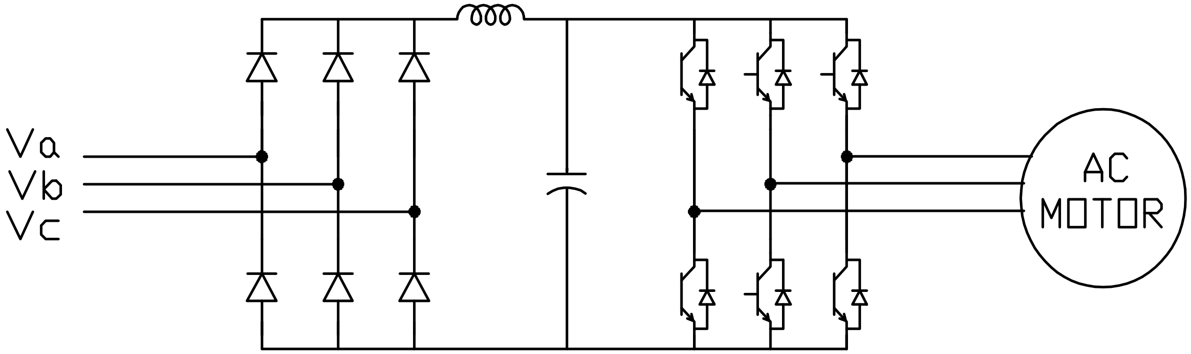


Characteristics and Applications:

- simple design, can handle multiple motors
- input (true) power factor can be poor due to high harmonic distortion of input currents
- is now being replaced in popularity by PWM type

Motor Voltage & Current

ASD Types - PWM Inverter



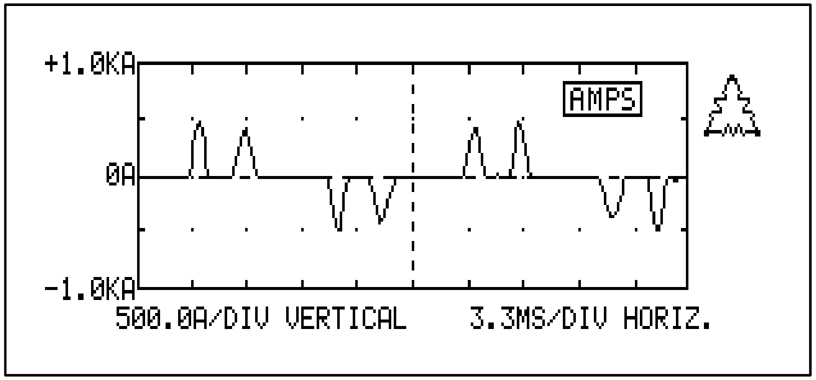
Characteristics and Applications:

Motor Voltage & Current

- used in all types of applications (e.g. HVAC) for motors < 500 Hp
- rectifier operates uncontrolled
- input currents can have high harmonic distortion, causing poor (true) power factor
- may be very sensitive to transient voltages on ac system

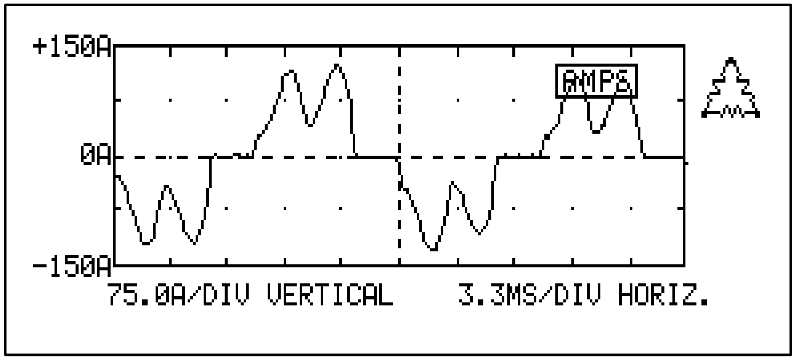
PWM Drive - Snapshot #1

PWM ASD with small (or no) input choke:

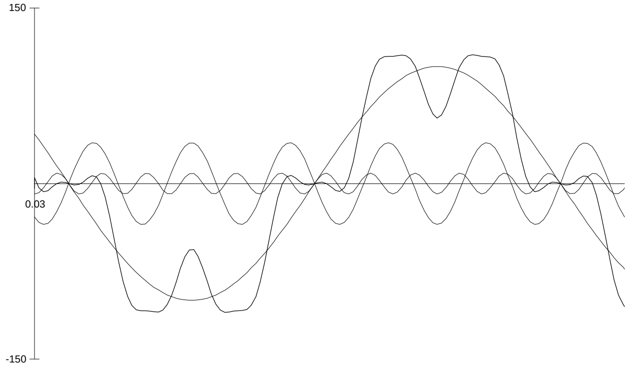


PWM Drive - Snapshot #2

PWM ASD with approximately 3% input choke:



Harmonic Distortion - Definition



Standards for Harmonics

IEEE 519-1992:

- Harmonic current injection limits for individual customers
- Harmonic voltage distortion limits for the overall system

IEC 555-2:

- Harmonic current injection limits for individual loads under 16 amps

ANSI/IEEE C57.110-1991:

- Transformer derating requirements

IEEE 519-1992 - What Does it Mean?

Harmonic Current Limits - Customer Responsibility

Isc/I(load)	<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

Values shown are in percent of rated load current

SCR = short circuit ration (utility short circuit current at point of common coupling divided by customer "rated" load current

Harmonic Voltage Limits - Utility Responsibility

Bus Voltage	Maximum Individual Harmonic Component (%)	Maximum THD (%)
Below 69 kV	3.0%	5.0%
69 kV to 138 kV	1.5%	2.5%
Above 138 kV	1.0%	1.5%

Standards for Harmonics - cont

IEC 555-2:

Lighting Equipment
(Table C)

Harmonic Order	Maximum Percent
2	2%
3	30% (PF)
5	10%
7	7%
9	5%
11-39	3%

Power Supplies
(Table D)

	Relative (mA/W)	Absolute (A)
Odd Harmonics		
3	3.6	1.08
5	2	0.6
7	1.5	0.45
9	1	0.3
11-39	0.6 x (11/n)	0.18 x (11/n)
Even Harmonics		
2	1	0.3
4	0.5	0.15

Standards for Harmonics - cont

Transformer Derating Requirements:

- ANSI/IEEE Standard C57.110-1991
  - Derating method that starts with a given load current spectrum and then determines the amount of this current that would cause the same losses as a purely sinusoidal current.
- K - Factor
  - Ability of a transformer to withstand increased eddy current losses due to harmonic load current.

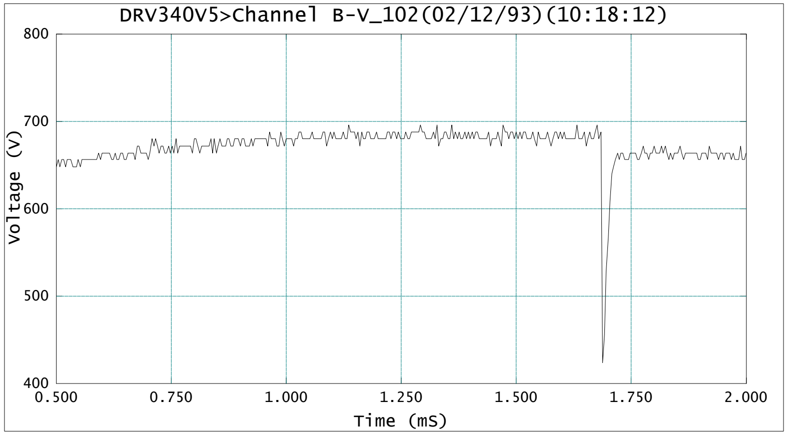
Sources of Harmonics

- Saturable devices - transformers and nonlinear reactors
- Arcing devices - arc furnaces, welders and fluorescent lighting
- Power electronics equipment - adjustable speed motor drives, dc motor drives and electronic power supplies

- Notching of the input voltage waves is a normal characteristic of the switching that occurs in the power electronics of a rectifier during continuous current operation.

Voltage Notching Snapshot

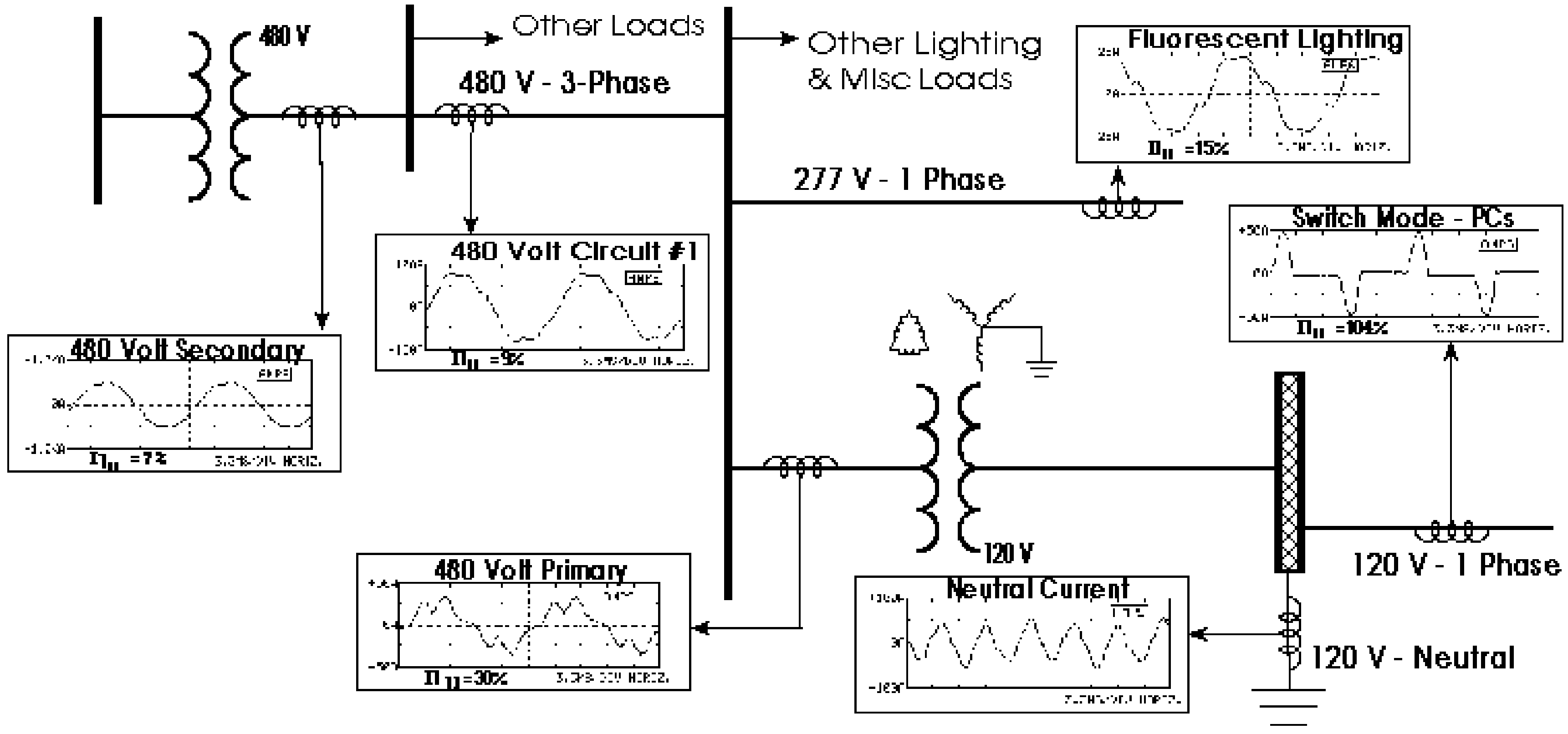
Expanded Waveform



Harmonics from Different Sources

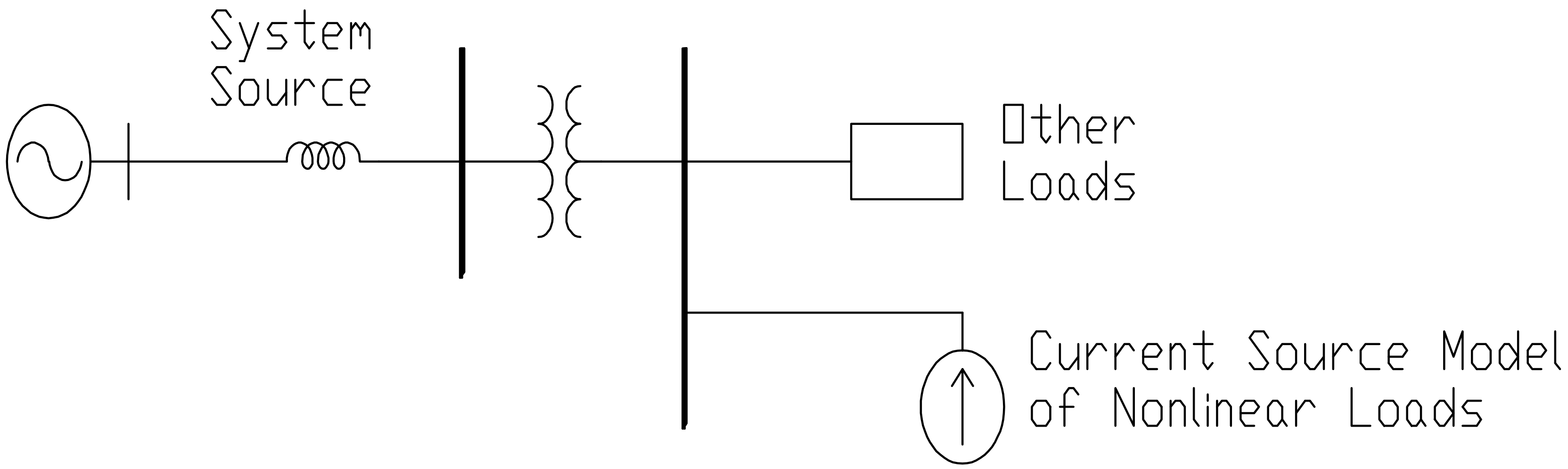
- Low-order (3,5,7) harmonic currents from multiple similar sources add nearly arithmetically.
- Higher-order harmonic currents will tend to cancel each other.
- Delta-wye transformer connections can have a significant influence on harmonic currents at the service entrance (especially 3^{rd}).

Harmonic Cancellation - Office Building

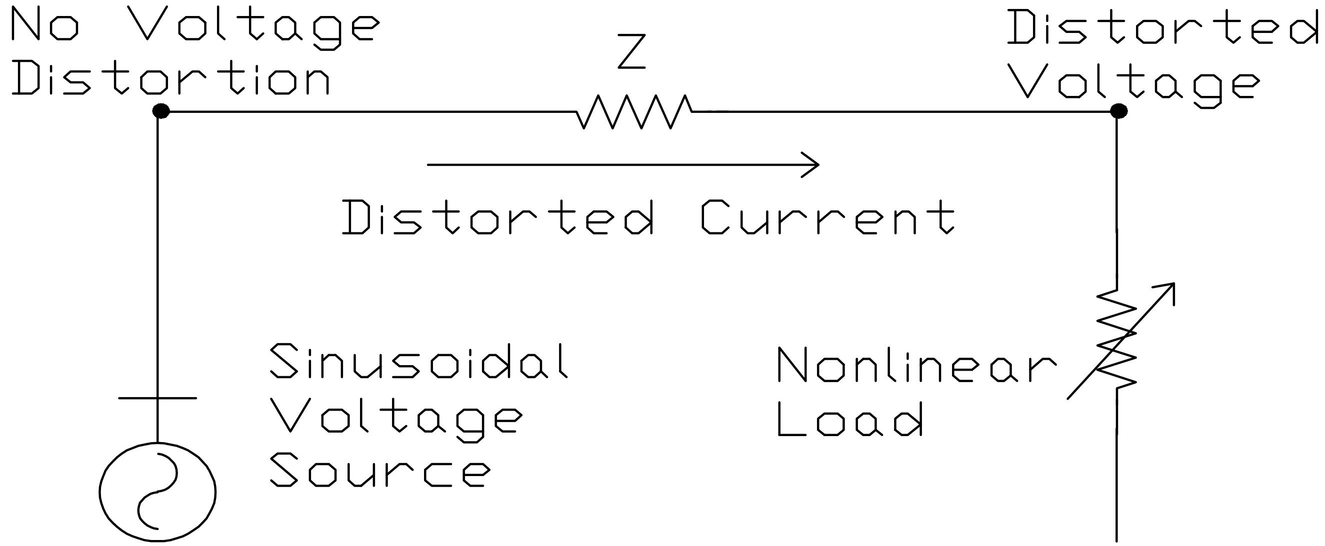


Representation of Nonlinear Loads

In general, a nonlinear load can be represented as a source of harmonic currents:



- Nonlinear loads inject harmonic current components onto the system.
- The system <u>impedance vs. frequency</u> characteristics determine the harmonic voltage distortion levels.



System Response Characteristics

- ☐ Voltage distortion is a result of the voltage drop created across the equivalent power system impedance.
- ☐ At 60 Hz, power systems are primarily inductive. The equivalent inductance can be calculated:

$$L_{eq} = \frac{X_{sc}}{2\pi * f}$$

X_{sc} = system short circuit reactance

f = power system fundamental frequency (60 Hz)

Local Impedance Calculation

- ❑ At utilization voltages, the equivalent system reactance is usually dominated by local impedances (the stepdown transformer).

- ❑ In general: $X_{sc} \approx X_{transformer}$

$$X_t = \frac{\left(kV_{LV}{}^2\right) * Z_{pu}}{MVA}\,\Omega$$

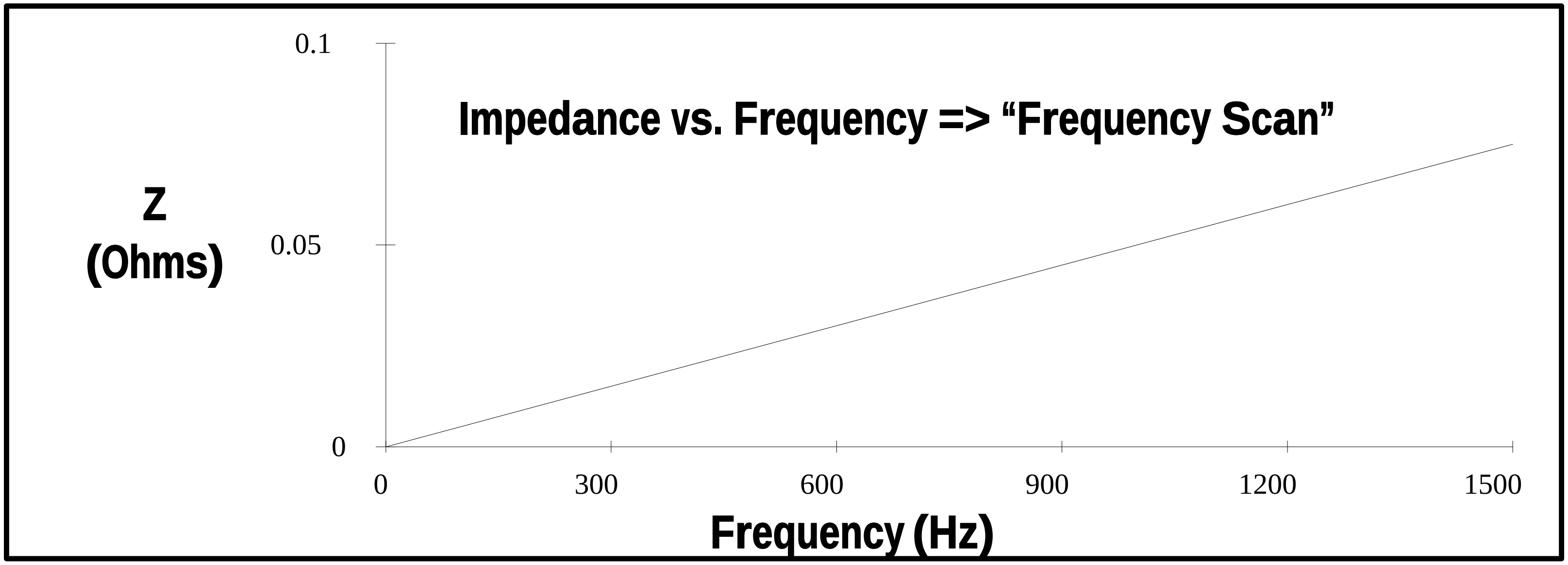
Impedance vs. Frequency

At harmonic frequencies, the impedance of the equivalent inductance is:

$$X_h = 2 \cdot p \cdot f_h \cdot L_{eq} = 2 \cdot p \cdot 60 \cdot h \cdot L_{eq}$$

h = harmonic number

f_h = harmonic frequency



Voltage Distortion Calculation

$$V_{THD} = \sqrt{\frac{\sum V_h^{\,2}}{V_1^{\,2}}}$$

500 HP Drive, 1500 kVA, 6% Transformer

Harmonic Number h	Harmonic Current (Amps) Ih	System Impedance (Ohms) Xh	Harmonic Voltage (Volts) Vh
5	186	0.046	8.55
7	38	0.064	2.43
11	61	0.101	6.16
13	28	0.119	3.33

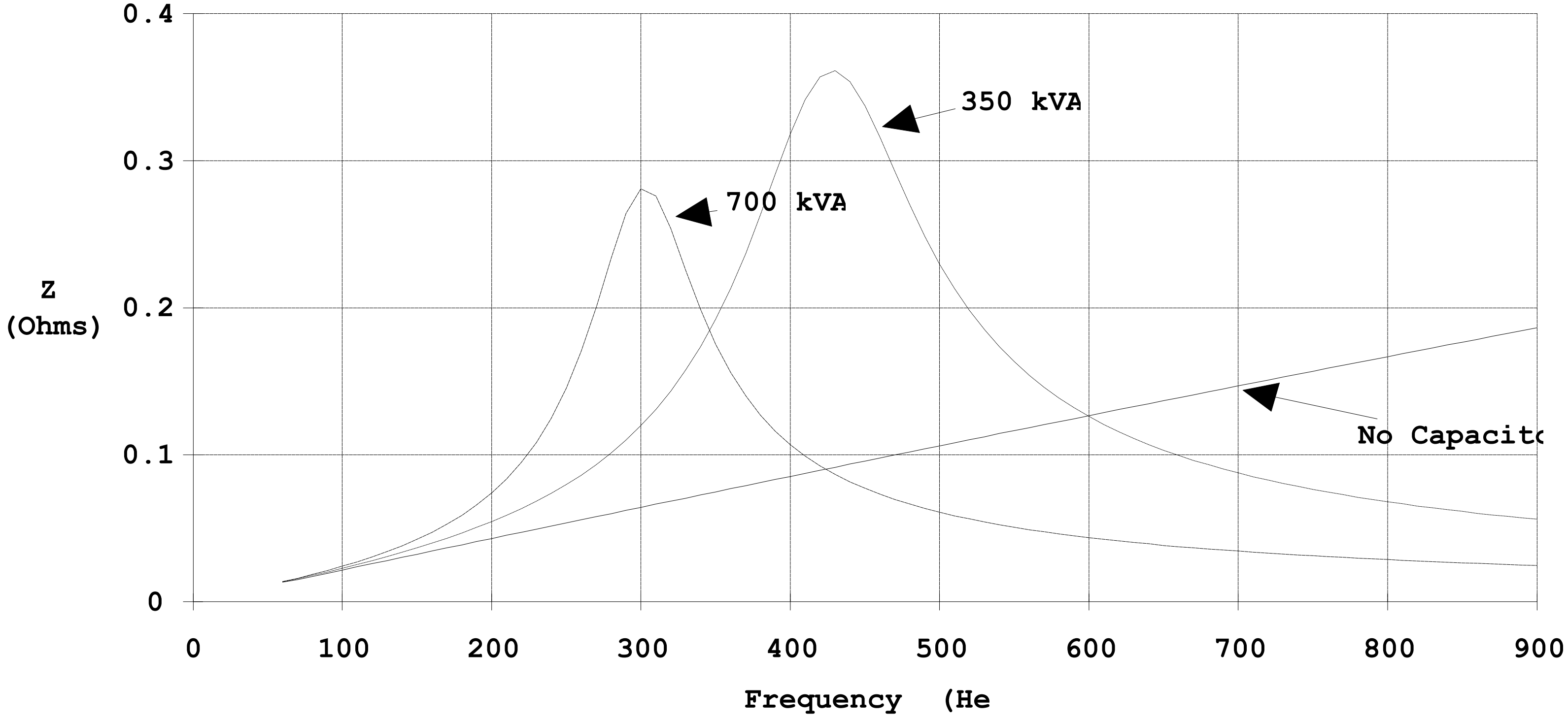
4.09%

$$V_{THD} = \sqrt{\frac{\left(8.55^2 + 2.43^2 + 6.16^2 + 3.33^2\right)}{\left(480/\sqrt{3}\right)^2}} = 4.09\%$$

Note: No capacitors installed

Effect of Shunt Capacitors

- Shunt capacitors can dramatically alter the system frequency response. They create a parallel resonance that can magnify harmonic currents and cause increased voltage distortion levels.



Resonant Frequency

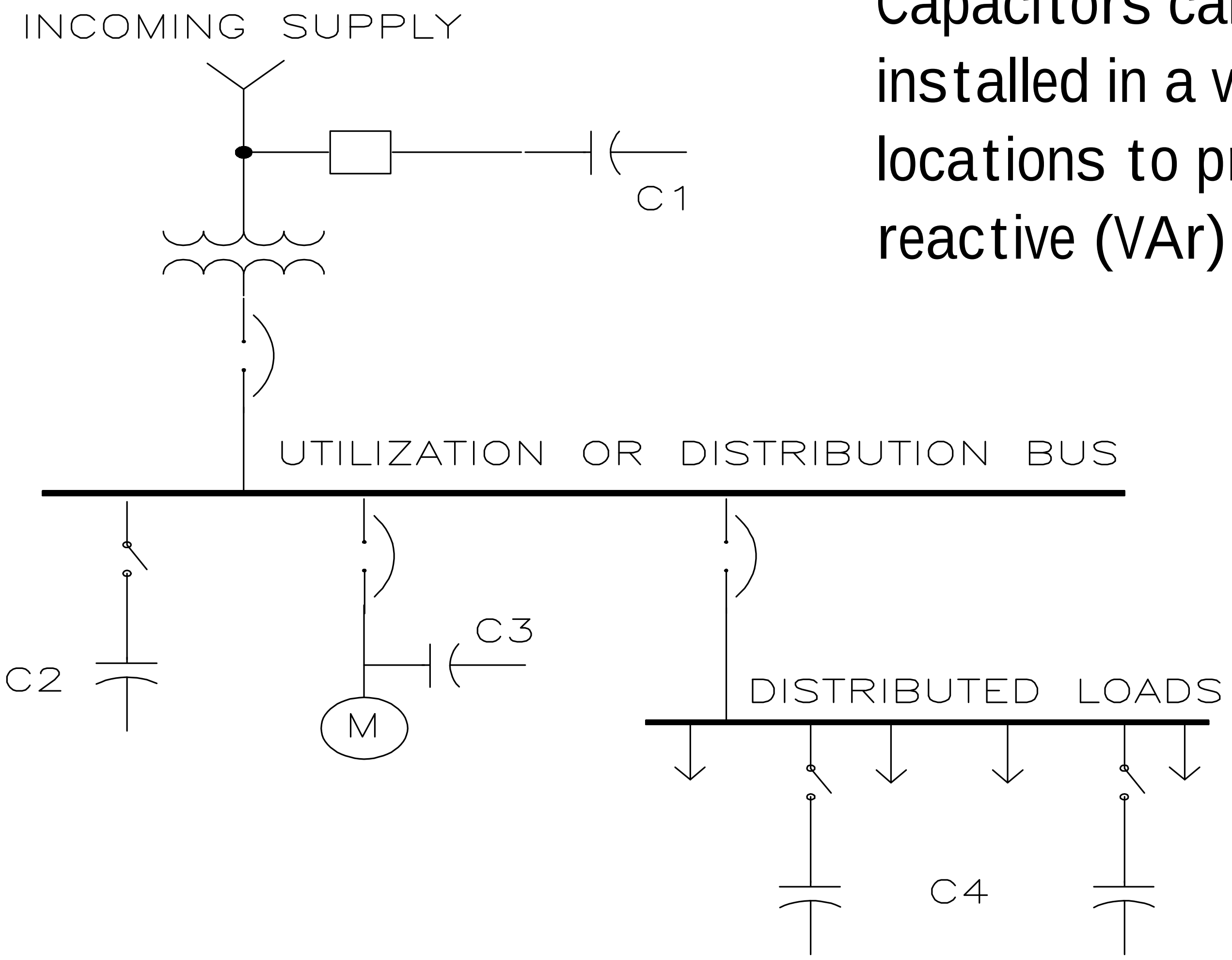
- At the frequency where the capacitive reactance (X_C) and the inductive reactance (X_L) are equal, the impedance seen by the nonlinear load becomes very large.

- This is known as the parallel resonant frequency and can be calculated from:

$$f_r = \frac{1}{2 \cdot p \cdot \sqrt{L \cdot C}} = \sqrt{\frac{MVA_{SC}}{MVAr_C}} \cdot 60$$

- If the **calculated frequency** corresponds to one of the **characteristic harmonic frequencies** of a nonlinear load, **high distortion** might be expected.

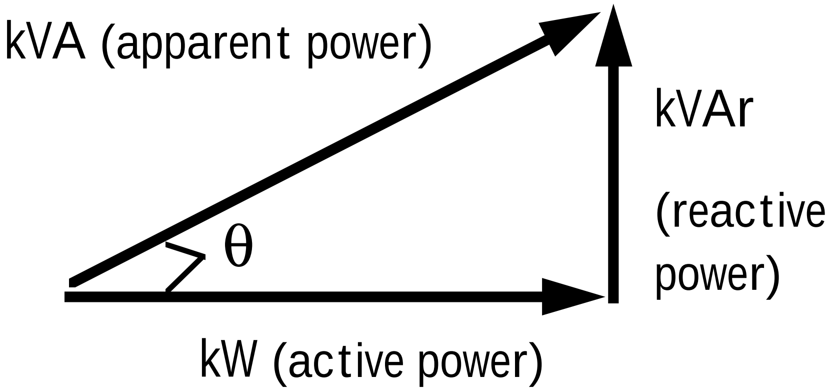
Location for Power Factor Correction



Capacitors can be installed in a variety of locations to provide reactive (VAr) power.

Displacement Power Factor Triangle

- Displacement Power Factor is only equal to the true power factor if the voltage and current waveforms contain zero harmonic distortion.



$$\mathrm{DPF} = \mathrm{Cos}\theta = \frac{\mathrm{kW}}{\mathrm{kVA}}$$

$$\mathrm{kVA} = \sqrt{\left(\mathrm{kW}^2 + \mathrm{kVAr}^2\right)}$$

Typical Power Factor of Loads

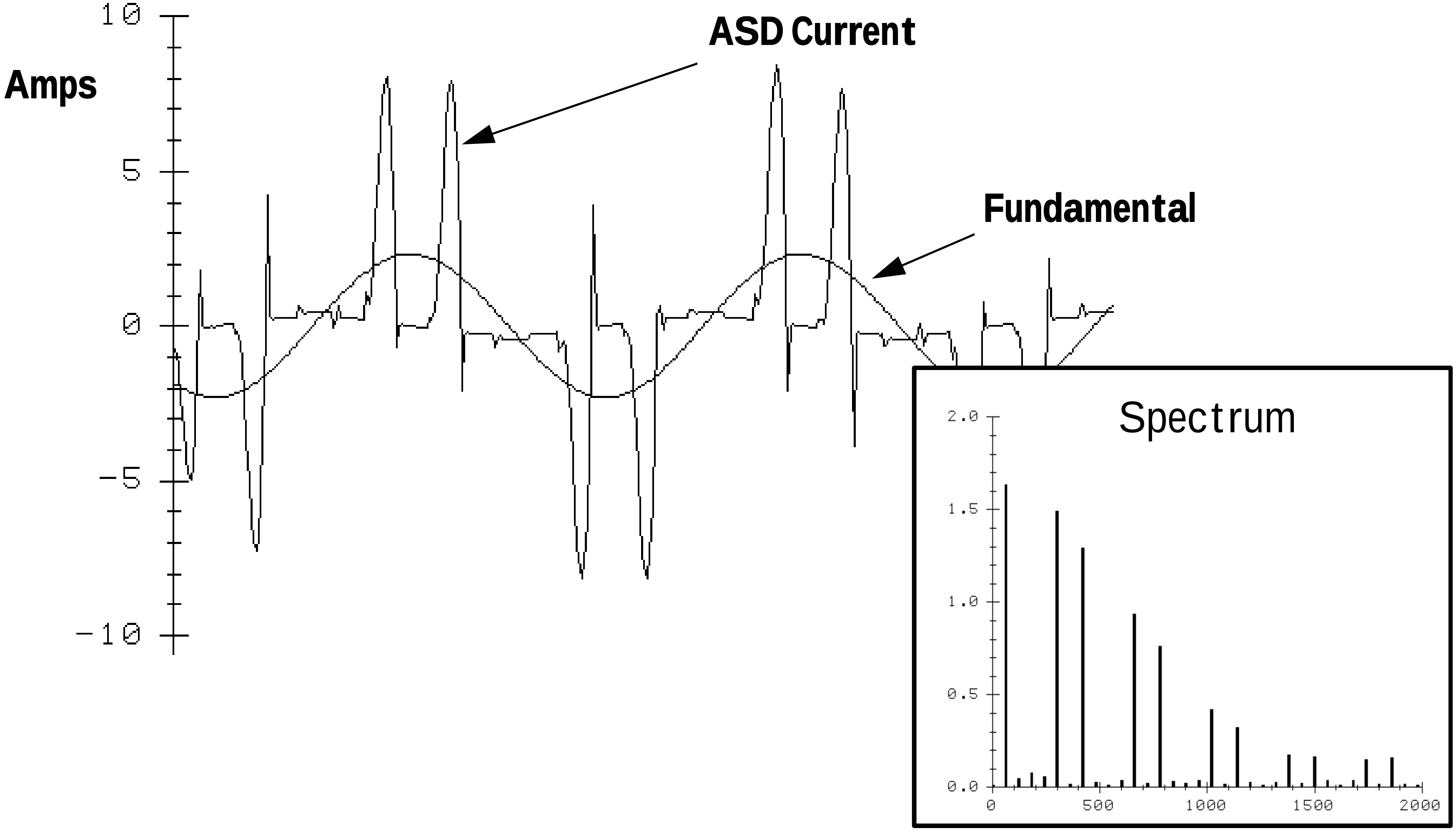
	Displacement Power Factor
Induction Motors	70-80
Diode Rectifiers (small ASDs)	95-98
Fluorescent Lighting	
Standard Ballast (also HID)	70
Electronic Ballast	90
Phase Controlled Rectifier (DC Drives) (Large ASDs)	40-90
Arc Furnaces	75-90
Arc Welding	35-60
Resistance Welding	40-60

True Power Factor - Definition

- Capacitors can only fully correct <u>displacement power factor</u> (only provide kVAr at fundamental frequency.)
- When harmonic currents or voltages are present, volt-amperes at the higher harmonic frequencies will decrease the <u>true power factor</u>.

An example follows using the line current and voltage of a small ASD.

ASD Line Current



Calculations for ASD Line Current

- ❑ The rms value of the ASD Line current (from the provided spectrum) is:

$$I_{rms} = \sqrt{\sum_{h=1}^{\infty} I_h{}^2} = \sqrt{\left(1.63^2 + 1.50^2 + \ldots + 0.17^2\right)} = 2.91 \text{ amps}$$

- ❑ Similarly the Total Harmonic Distortion (THD) can be calculated using:

$$\text{THD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \ldots}}{I_1} = \frac{2.414}{1.63} = 1.48 = 148\%$$

- ❑ And the Crest Factor (CF) is defined as:

$$\text{CF} = \frac{I_{peak}}{I_{rms}} = \frac{8.0}{2.913} = 2.746$$

True Power Factor Calculation

- ❑ For the ASD line current assume the fundamental component of the current is in phase with the voltage, therefore:

$$\theta = 0^\circ$$

- ▸ And the displacement power factor is equal to unity:

$$\text{DPF} = \cos\theta = 1.0 = 100\%$$

- ▸ The real power consumed (single phase, first order approximation) is:

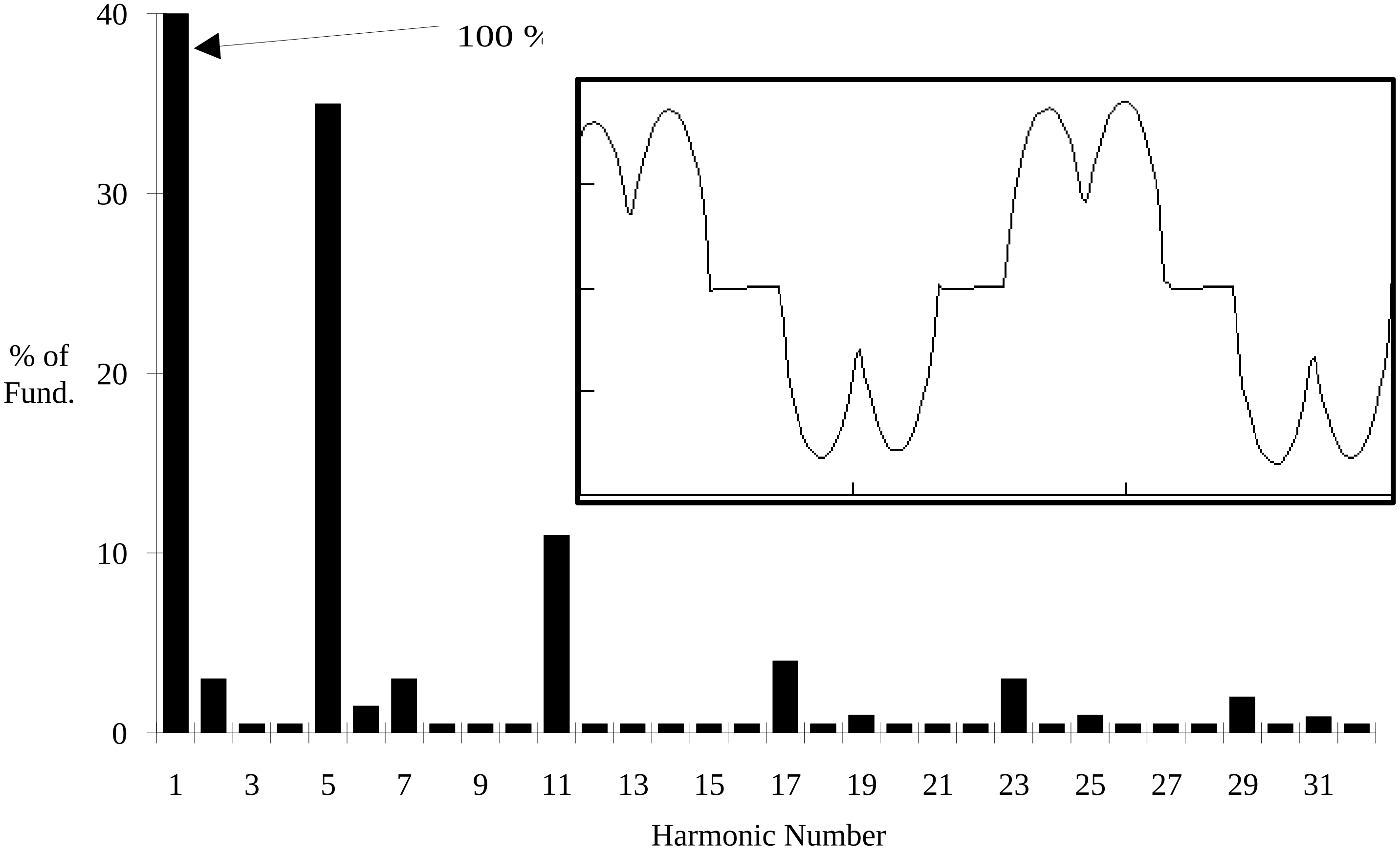
$$P = V_1 \cdot I_1 \cdot \cos\theta = (480\text{V})(1.63\text{A})(1.0) = 782.4\text{W}$$

- ▸ Finally, the true power factor is:

$$\text{TPF} = \frac{P}{V_{rms} \cdot I_{rms}} = \frac{782.4\text{W}}{(480\text{V})(2.913\text{A})} = 0.56 = \underline{\underline{56\%}}$$

Harmonic Waveform and Spectrum

Individual Frequencies and Magnitudes are Important!



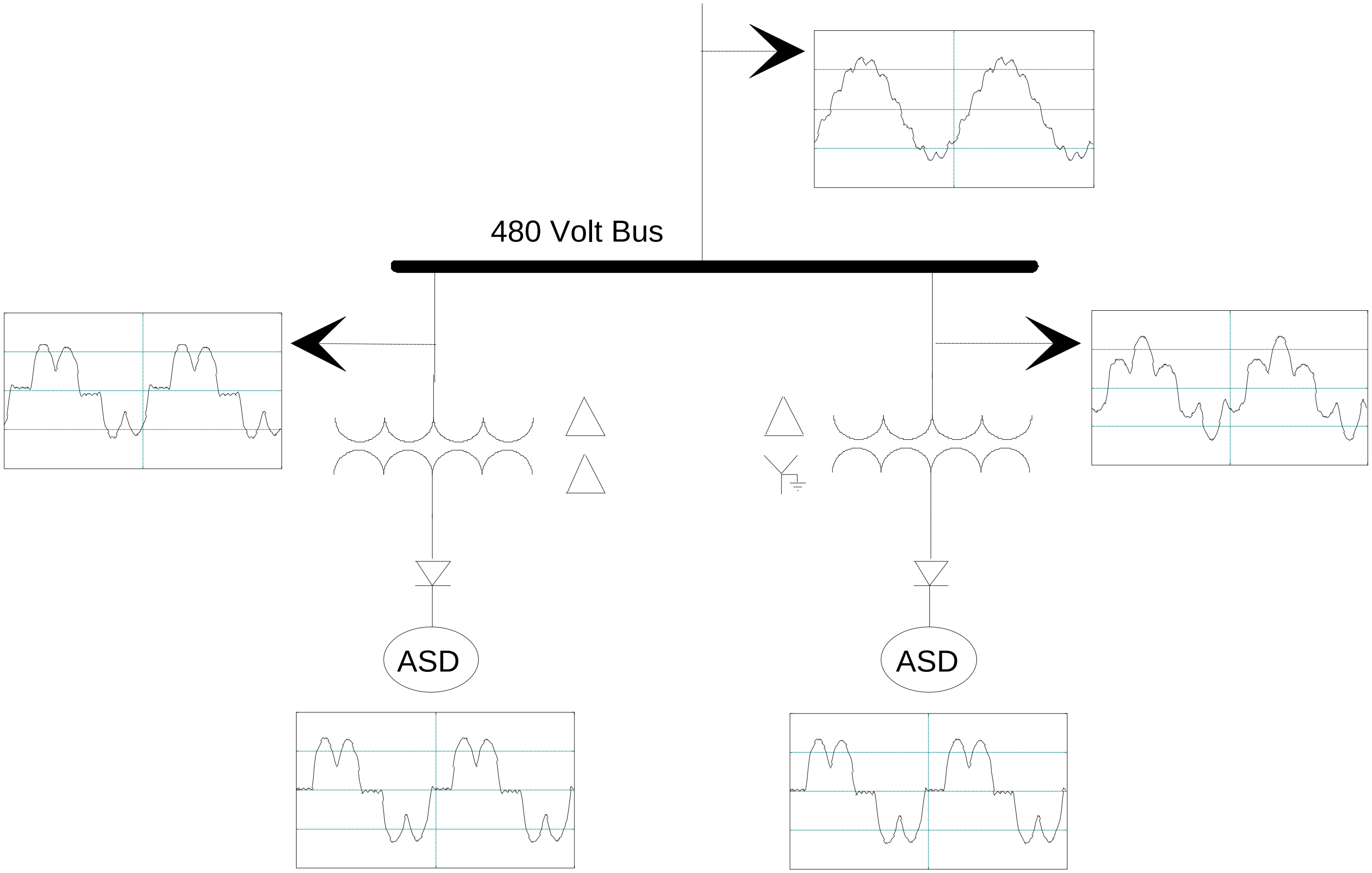
Harmonic Reduction Methods

ASD Input Current Waveform

ASD Input Current Waveform with 30° Phase Shift Through Isolation Transformer

Result is very good current distortion level, if approximately half of load is each waveform.

Impact of Transformer Connection



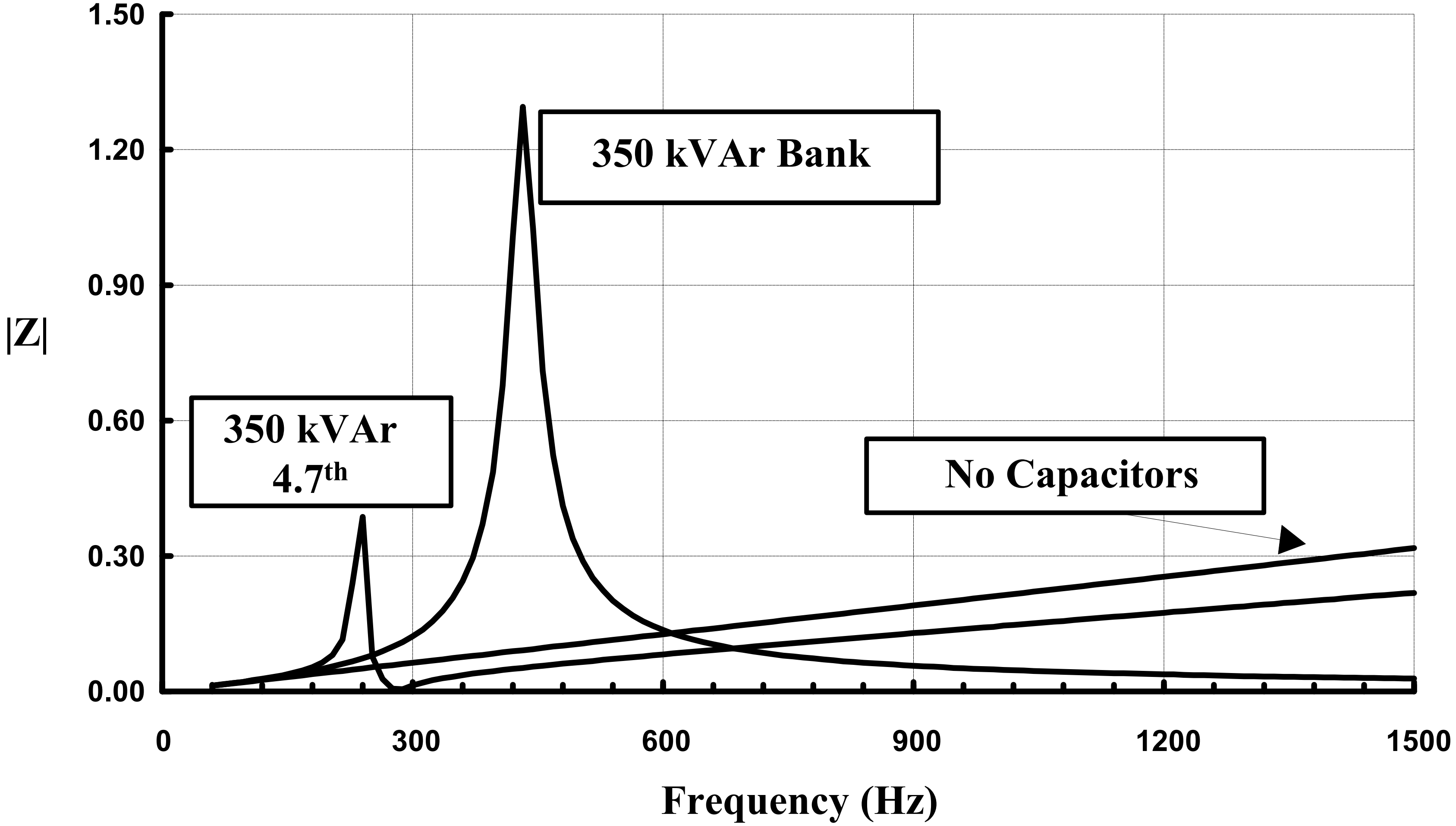
ISOXFMRS.SHA

Reduction Methods - Basic Filter Design

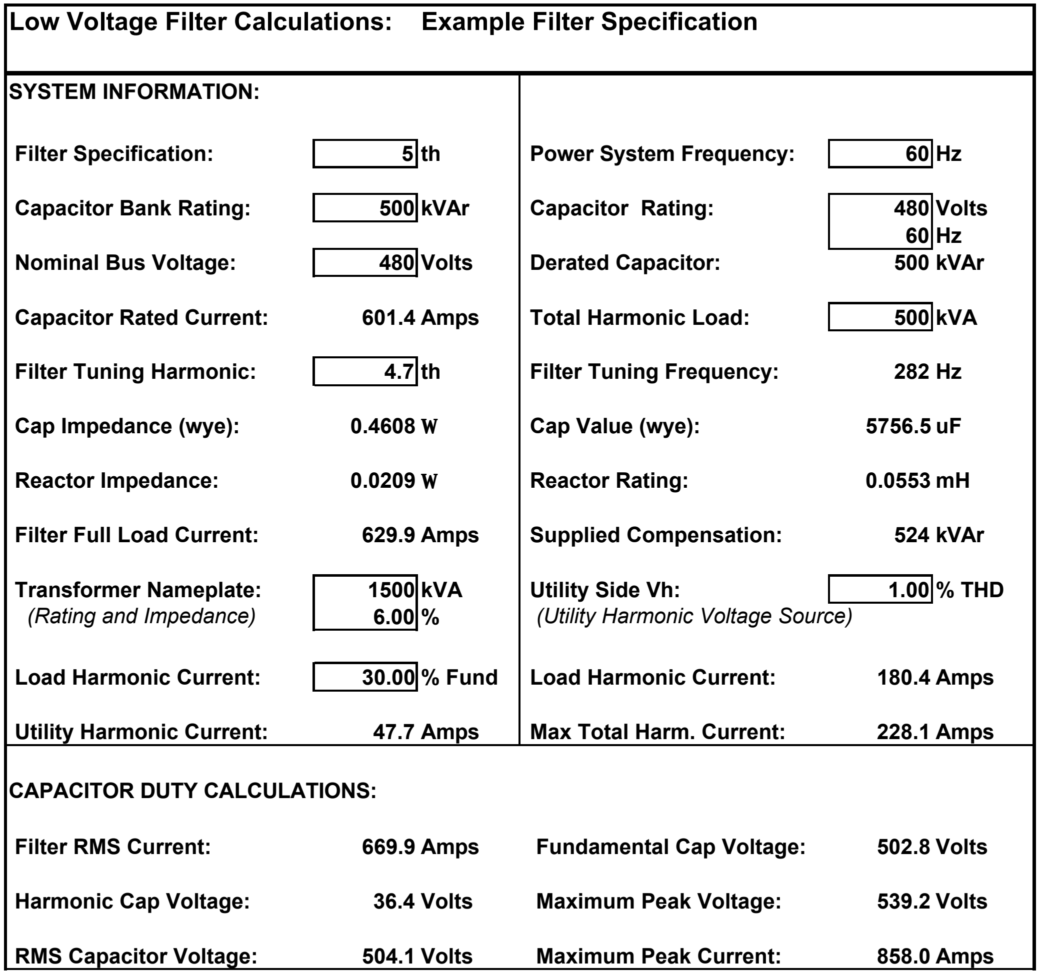
The general method for applying filters is as follows:

- ❑ Apply one single tuned filter first, and design it for the lowest generated frequency (i.e. 5th harmonic - 4.7th filter).
- ❑ Determine the voltage distortion at the low voltage bus, 5% is the commonly applied limit.
- ❑ Vary filter elements (tolerances) and check its effectiveness.
- ❑ Check the frequency response characteristic to verify that the newly created parallel resonance is not close to a harmonic frequency.
- ❑ If necessary, investigate the need for several filters, such as 5th and 7th.

Effect of Filter on Frequency Response



Example Filter Design Spreadsheet



Low Voltage Filter Calculations: Example Filter Specification

SYSTEM INFORMATION:

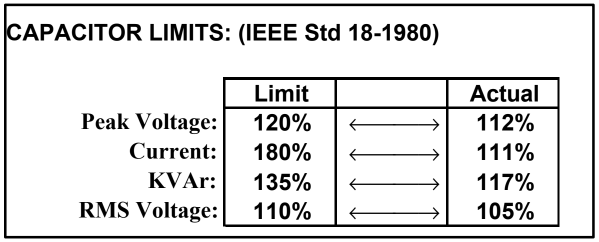
Filter Specification:	5	th	Power System Frequency:	60	Hz
Capacitor Bank Rating:	500	kVAr	Capacitor Rating:	480 60	Volts Hz
Nominal Bus Voltage:	480	Volts	Derated Capacitor:	500	kVAr
Capacitor Rated Current:	601.4	Amps	Total Harmonic Load:	500	kVA
Filter Tuning Harmonic:	4.7	th	Filter Tuning Frequency:	282	Hz
Cap Impedance (wye):	0.4608	W	Cap Value (wye):	5756.5	uF
Reactor Impedance:	0.0209	W	Reactor Rating:	0.0553	mH
Filter Full Load Current:	629.9	Amps	Supplied Compensation:	524	kVAr
Transformer Nameplate: *(Rating and Impedance)*	1500 6.00	kVA %	Utility Side Vh: *(Utility Harmonic Voltage Source)*	1.00	% THD
Load Harmonic Current:	30.00	% Fund	Load Harmonic Current:	180.4	Amps
Utility Harmonic Current:	47.7	Amps	Max Total Harm. Current:	228.1	Amps

CAPACITOR DUTY CALCULATIONS:

Filter RMS Current:	669.9	Amps	Fundamental Cap Voltage:	502.8	Volts
Harmonic Cap Voltage:	36.4	Volts	Maximum Peak Voltage:	539.2	Volts
RMS Capacitor Voltage:	504.1	Volts	Maximum Peak Current:	858.0	Amps

Important Parameters:

- Capacitor Size and Voltage
- Tuning Frequency
- Reactor Impedance
- Capacitor Limits
- Reactor Current Rating (60 Hz and Harmonic)



CAPACITOR LIMITS: (IEEE Std 18-1980)

	Limit		Actual
Peak Voltage:	120%	⟷	112%
Current:	180%	⟷	111%
KVAr:	135%	⟷	117%
RMS Voltage:	110%	⟷	105%

Harmonic Filter Design - Case Study

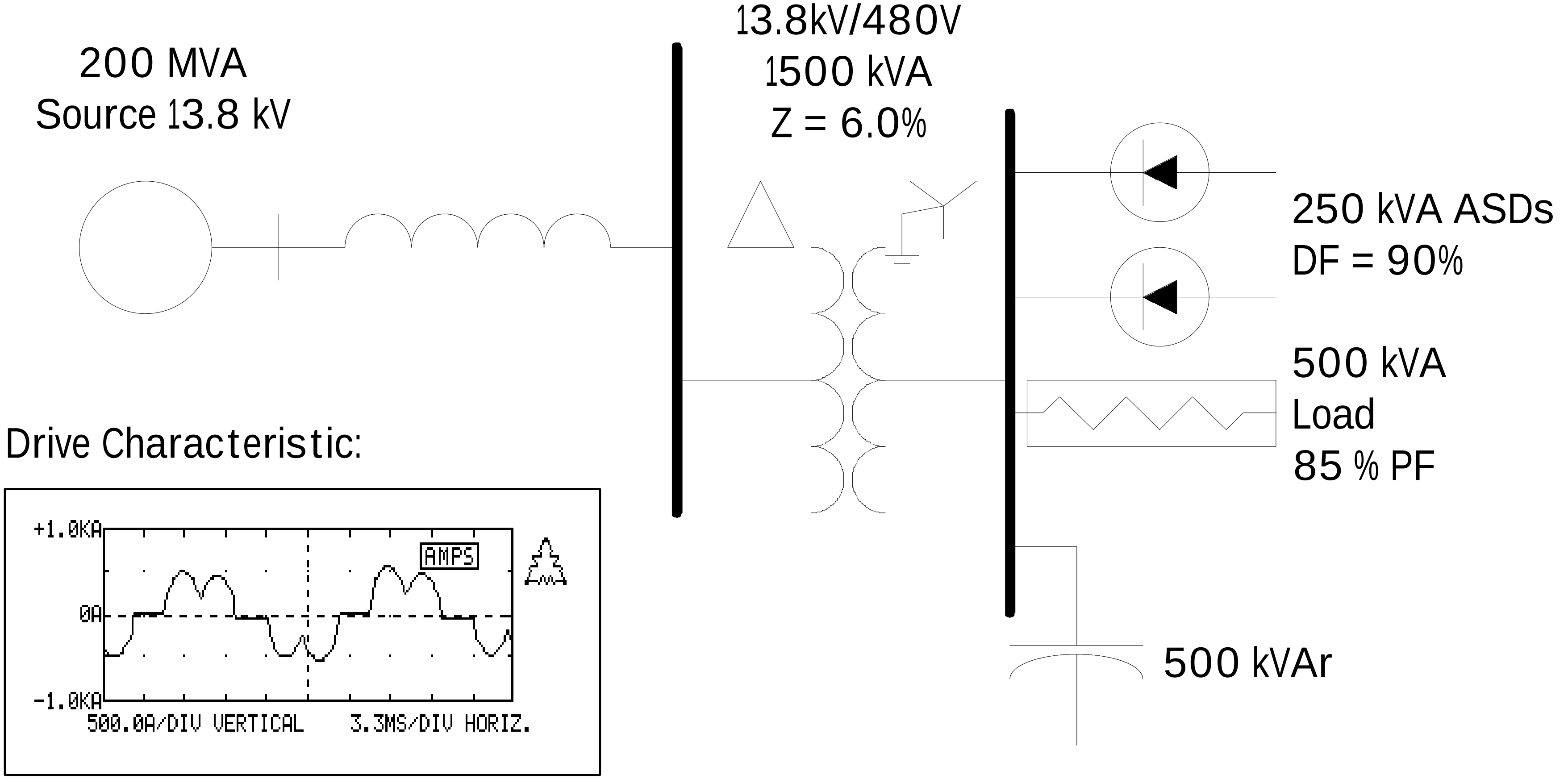
- **Problem Statement:** A plastics manufacturer is experiencing equipment problems, including capacitor bank fuses blowing, and a capacitor can failure. The plant engineer believes that the problem may be related to harmonics. He measures the following bus voltage waveform:

[redacted]

Oneline for Harmonic Analysis

Circuit for harmonic analysis:

FILTER_1.SHA



200 MVA
Source 13.8 kV

13.8kV/480V
1500 kVA
Z = 6.0%

250 kVA ASDs
DF = 90%

500 kVA
Load
85 % PF

500 kVAr

Drive Characteristic:

SuperHarm Data Listing

Comment Section and Titles (TITLE)

```
//
//      File Name:  FILTER_1.SHA
//
//      HarmFlo+ Case Study Workbook - Volume #2, Draft #1
//
//      Industrial case study.  Plant has one 480 Volt bus that
//      feeds two 250 kVA ASDs and 500 kVA of additional motor
//      and other miscellaneous loads.  Plant engineers are proposing
//      to add 500 kVAr of power factor correction to increase power factor
//      and to free up some transformer kVA.
//
//      This model is a single phase representation of the Utilty system
//      and the plant.  All values are in single phase quantities.
//

TITLE           TITLE1 = "Industrial Filter Design Case Study"
                TITLE2 = "HarmFlo+ Case Study Workbook - Volume 2"
```

SuperHarm Data Listing - cont

Source Equivalent (VSOURCE and BRANCH)

```
//
//      Utility source, 200 MVA @ 13.8 kV
//

VSOURCE         NAME = UTILSRC
                BUS = SRC       FREQ = 60.0
                MAG = 7967      ANG = 0.0

//
//      Positive sequence source equivalent @ service entrance.
//      All values in Ohms.  X to R ratio = 20
//

BRANCH          NAME = ZEQ
                FROM = SRC      TO = SERVENT
                R = 0.04761     X = 0.9522
```

SuperHarm Data Listing - cont

Transformer Model (TRANSFORMER)

```
//
//      Step down transformer @ service entrance.
//      1500 kVA, 13.8 kV / 480 Volt, Z = 6 %
//
//      The "@" symbol is used to do inline math.  In this case
//      the Line to Ground voltage is calculated from the Line to Line
//      voltage.
//

TRANSFORMER     NAME = STEPTRAN MVAB.HX = 0.500
                X.1 = 480BUS    X.2 = GROUND
                H.1 = SERVENT   H.2 = GROUND
                %X.HX = 6.0     KV.X = @"0.480 3 SQRT /"
                KV.H = @"13.8 3 SQRT /"
```

SuperHarm Data Listing - cont

Miscellaneous Load Model (LINEARLOAD)

```
//
//      Miscellaneous load on 480 Volt bus.
//      Using the Linear Load model
//      500 kVA of load.  166 kVA of single phase load.
//

LINEARLOAD      NAME = MISCLOAD
                FROM = 480BUS   TO = GROUND
                KV = 0.277      KVA = 166
                DF = 0.85       %PARALLEL = 90.0
                %SERIES = 10.0
```

ASD Characteristic

Adjustable-speed drive characteristic:

Total Drive rating:	500	Hp
Voltage:	480	V
Fundamental Current:	600	A

Harmonic	%	Amps
5	33.6	202
7	1.6	9.6
11	8.7	52.2
13	1.2	7.2

$$\mathrm{THD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \ldots}}{I_1}:$$

$$I_{THD} = 34.8\%$$

SuperHarm Data Listing - cont

ASD Models (NONLINEARLOAD)

```
//
//      Model of the ASDs on the 480 Volt bus.
//      2 - 250 kVA ASDs running full load & 75% pf
//      Using the NonLinear Load model.
//

NONLINEARLOAD   NAME = ASD1
                BUS = 480BUS
                KV = 0.277      KVA = 83.0      DF = 0.75
                TABLE = {
                        { 1,    100.0,   -75.0},
                        { 5,     33.6,   156.0},
                        { 7,      1.6,  -151.0},
                        {11,      8.7,  -131.0},
                        {13,      1.2,    54.0},
                        {17,      4.5,   -57.0},
                        {19,      1.3,  -226.0},
                        {23,      2.7,    17.0},
                        {25,      1.2,  -149.0}
                        }
```

SuperHarm Data Listing - cont

Frequency Scan (SCAN)

```
//
//      Frequency Scan Request (remove comment to activate)
//

//      SCAN    Name = Scan1
//              BUS = 480BUS    ANG = 0
//              FMIN = 60       FMAX = 1500     FINC = 10
```

Insert SCAN card in data file and SuperHarm will short all other sources and open all injected currents and perform a frequency scan at that bus.

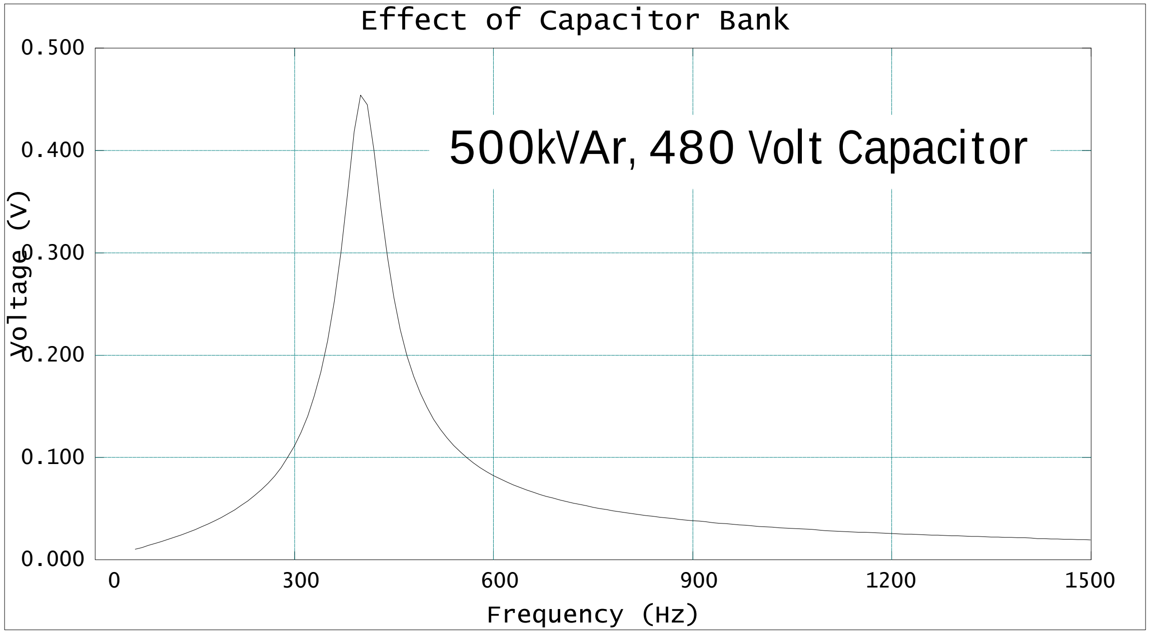
Voltage Distortion - No Capacitors

h	I_h	$X_h = h*X_t$	$V_h = I_h*X_h$
5	**202**	**0.046**	**9.29**
7	9.6	0.064	0.62
11	52	0.101	5.25
13	7.2	0.119	0.86

$$V_{THD} = \sqrt{\frac{\left(9.29^2 + 0.62^2 + 5.25^2 + 0.86^2\right)}{277^2}} = 3.87\%$$

Effect of 500 kVAr Capacitor Bank

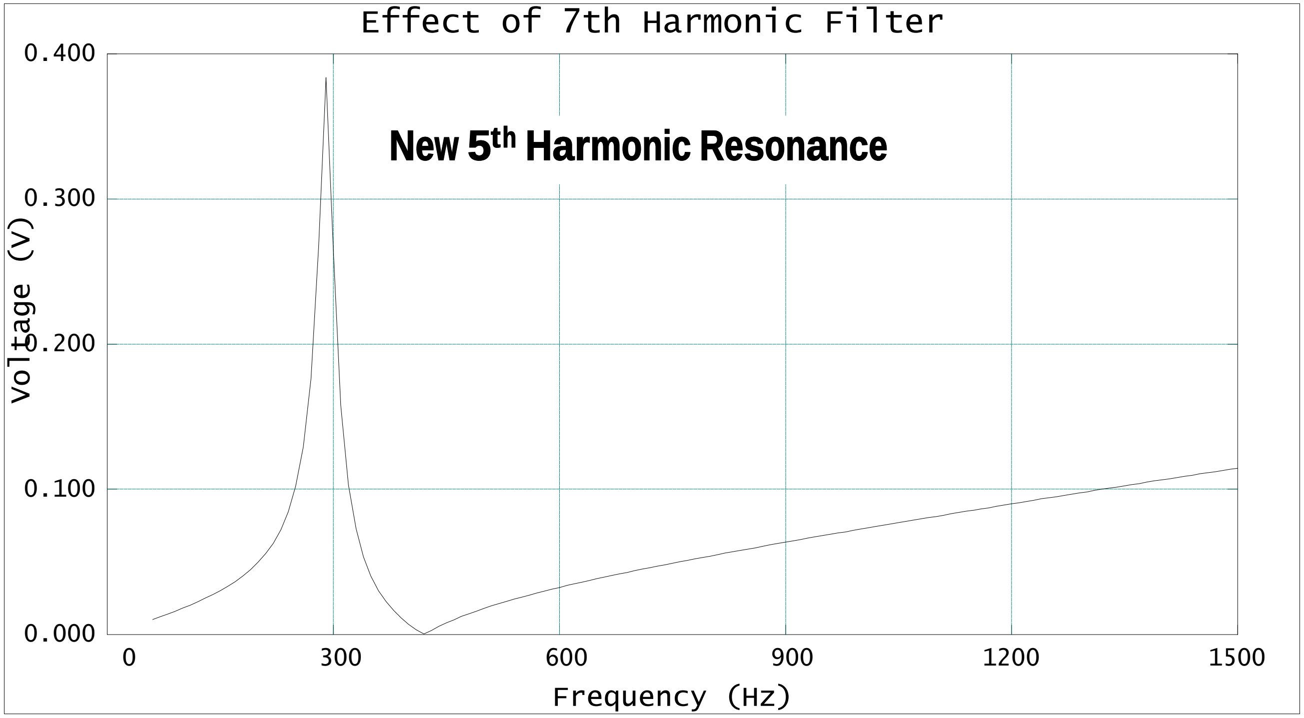
The 500 kVAr capacitor bank causes a resonance near the 7th harmonic, which can be calculated from the following equation and illustrated in the following plot. The distortion level increased to 8.29% with the addition of the bank.



Initial Solution?

would appear to be the application of a 7th harmonic filter.

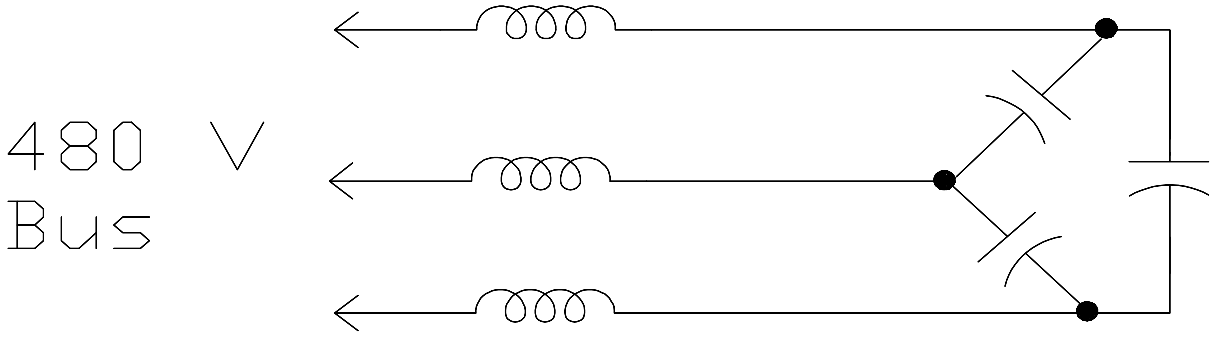
The distortion increased to <u>19.6%</u>!



Final Solution

- In general, it is best to apply the filter at or below the lowest harmonic of concern.
- In this case, a 5th harmonic filter, tuned to 4.7, reduces the 480 volt bus voltage distortion to 2.13%.
- The filter connections are shown below:

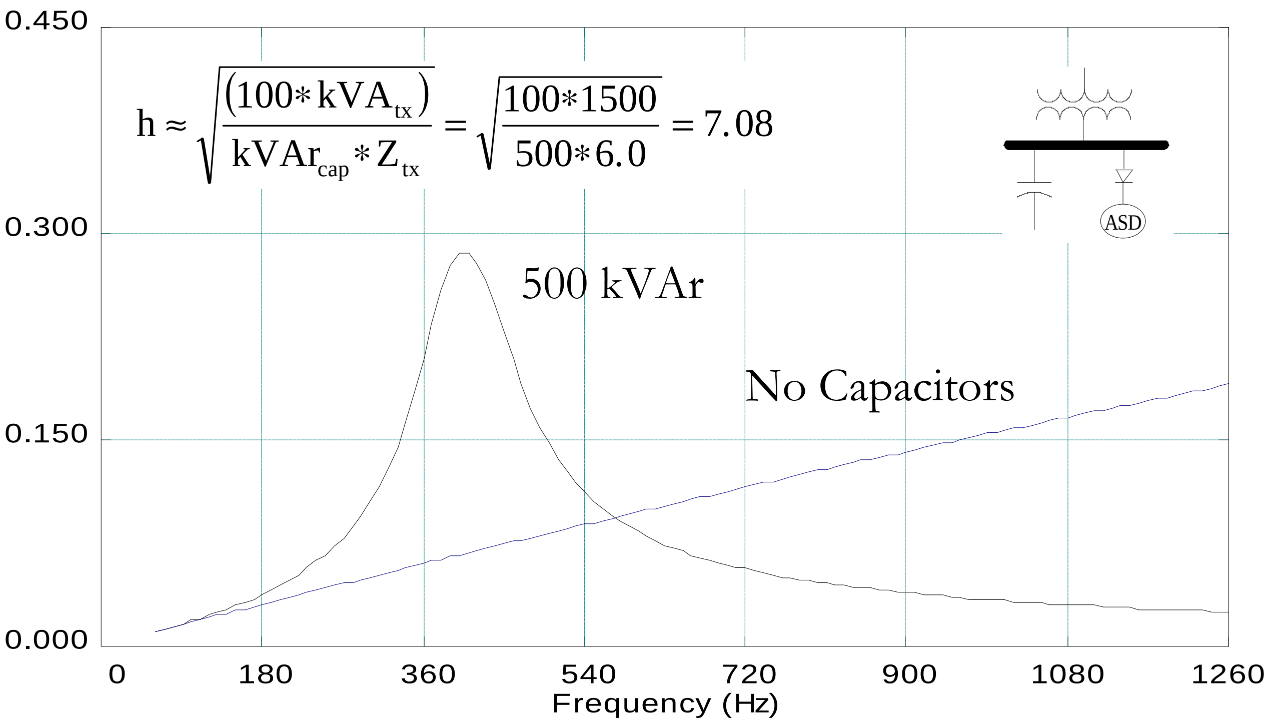
$X_l = 0.0209\ \Omega$ & $X_c = 0.460\ \Omega$



500 kVAr @ 480 Volt

Industrial Tech Brief Case Study

- ❑ Preliminary Analysis / Model Development



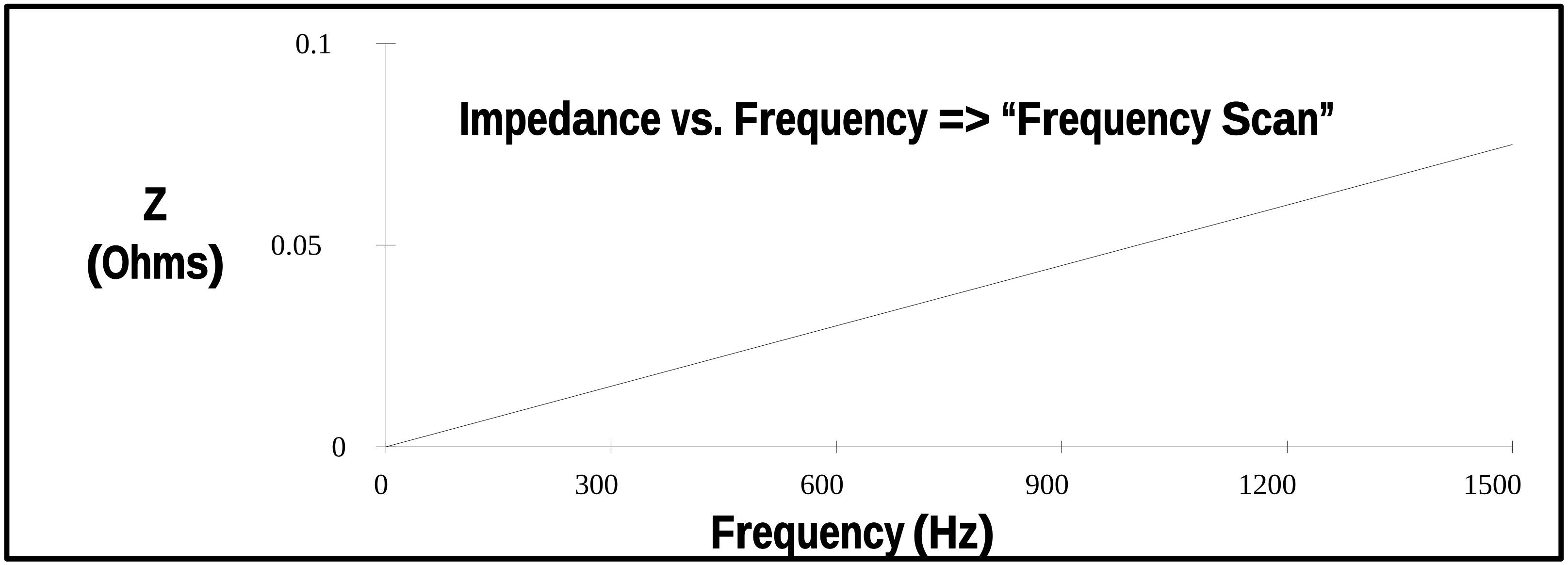
$$h \approx \sqrt{\frac{(100 * kVA_{tx})}{kVAr_{cap} * Z_{tx}}} = \sqrt{\frac{100 * 1500}{500 * 6.0}} = 7.08$$

Industrial Tech Brief Case Study - cont

- Performing Harmonic Measurements
  - Determine harmonic source characteristics
    - Waveform
    - Spectrum
  - Verify harmonic simulation model
    - Use current spectrum from measurement
    - Compare simulated and measured voltage distortion levels
  - Statistical Characteristics

Industrial Tech Brief Case Study - cont

- Performing Simulations

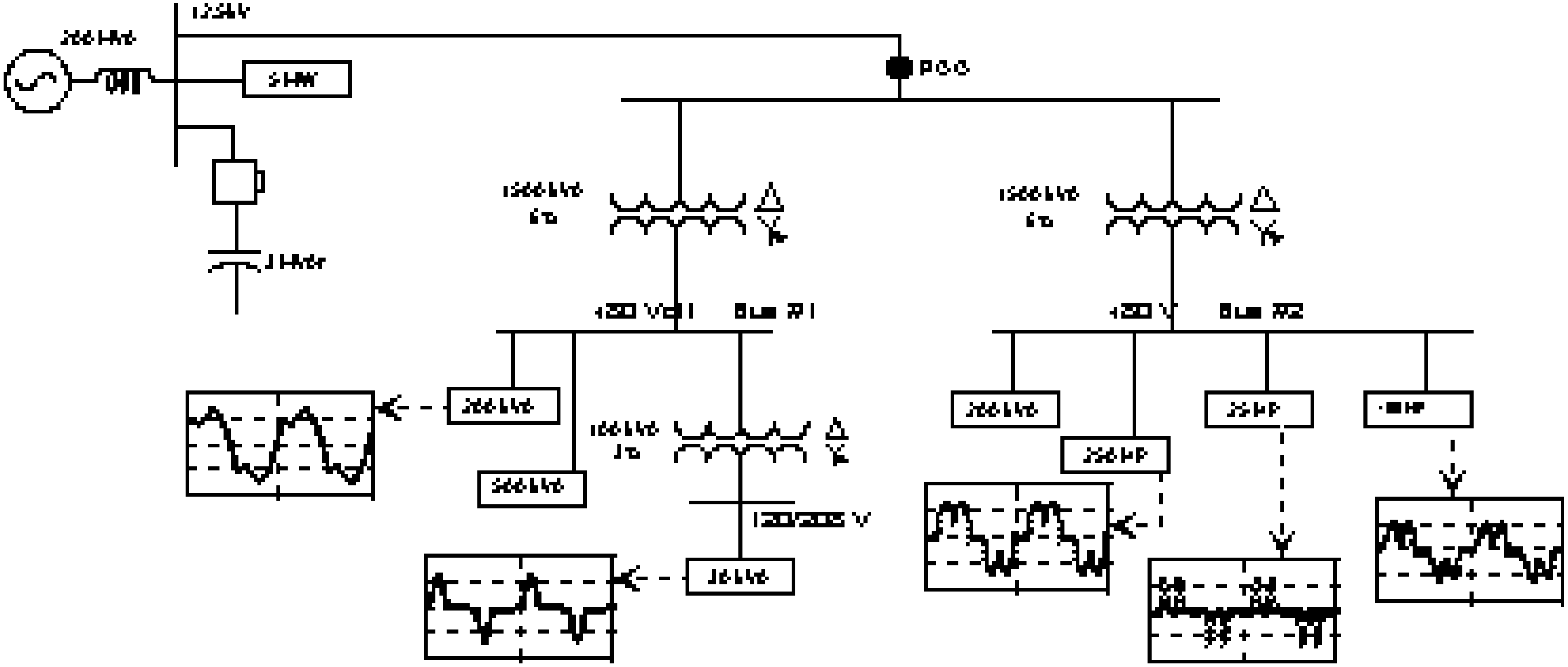


SuperHarm Data File

```
//
//      File Name:  HARMTECH.SHA
//
//      HarmFlo+ Case Study Workbook - Volume #3, Draft #1
//
//      Case Study for EPRI Harmonic Tech Brief
//      Investigation of harmonic concerns in industrial plants
//
//      This model is a three-phase representation of the power
    system.
//      All values are in three-phase quantities.
//

TITLE           TITLE1 = "Harmonics Tech Brief Case Study"
                TITLE2 = "HarmFlo+ Case Study Workbook - Volume 3"
```

Industrial Tech Brief Case Study - cont



Industrial Tech Brief Case Study - cont

- System Parameters
  - 12.5kV Source Strength: 200 MVA (0.78Ω)
  - 12.5kV Capacitor Size: 3 MVAr
  - 12.5kV Feeder Load: 5 MW
  - Distribution Feeder Impedance: 0.2Ω

SuperHarm Data File - cont

```
//      Miscellaneous load on 12.5kV Substation Bus
//      Using the Linear Load model
//      5000 kVA of load.  1660 kVA of single phase load.

LINEARLOAD      NAME = SUBL1A
                FROM = 12_5A    TO = GROUND
                KV = 7.216      KVA = 1660
                DF = 0.90       %PARALLEL = 100.0

LINEARLOAD      NAME = SUBL1B
                FROM = 12_5C    TO = GROUND
                KV = 7.216      KVA = 1660
                DF = 0.90       %PARALLEL = 100.0

LINEARLOAD      NAME = SUBL1C
                FROM = 12_5C    TO = GROUND
                KV = 7.216      KVA = 1660
                DF = 0.90       %PARALLEL = 100.0
```

Industrial Tech Brief Case Study - cont

- ❑ Plant Load Summary

Fluorescent Lighting (THD=21.7%):	200 kVA
dc Drive (THD=35.2%):	250 HP
PWM ASD - no choke (THD=130.7%)	25 HP
PWM ASD - 3% choke (THD=45.1%)	100 HP

SuperHarm Data File - cont

```
//
//      250 kVAr, 480 Volt Power Factor Correction Capacitor Bank
//      Installed on 480 Volt Bus #2
//

CAPACITOR       NAME = PFCAP2A
                FROM = 4802A    TO = GROUND
                KV = 0.277      MVA = 0.06667

CAPACITOR       NAME = PFCAP2B
                FROM = 4802B    TO = GROUND
                KV = 0.277      MVA = 0.06667

CAPACITOR       NAME = PFCAP2C
                FROM = 4802C    TO = GROUND
                KV = 0.277      MVA = 0.06667
```

Industrial Tech Brief Case Study - cont

Harmonic Current Evaluation - Case #1 - (basecase, no power factor correction)

	5th	**7th**	**11th**	**13th**	**17th**	**19th**	**23rd**	**25th**	**TDD**
519	5.4	5.4	2.5	2.5	2.5	2.3	0.9	0.9	6.8
Actual	3.1	1.3	0.9	0.5	0.5	0.2	0.4	0.1	4.2
Exceed	No	No	No	No	No	No	No	No	No

Harmonic Current Evaluation - Case #2 - (with 200 kVAr power factor correction)

	5th	**7th**	**11th**	**13th**	**17th**	**19th**	**23rd**	**25th**	**TDD**
519	5.4	5.4	2.5	2.5	2.5	2.3	0.9	0.9	6.8
Actual	4.1	2.4	2.9	0.8	0.3	0.1	0.1	0.1	5.3
Exceed	No	No	Yes	No	No	No	No	No	No

Harmonic Current Evaluation - Case #3 - (with 200 kVAr, 4.7th harmonic filters)

	5th	**7th**	**11th**	**13th**	**17th**	**19th**	**23rd**	**25th**	**TDD**
519	5.4	5.4	2.5	2.5	2.5	2.3	0.9	0.9	6.8
Actual	1.1	0.9	0.7	0.4	0.4	0.2	0.3	0.1	2.9
Exceed	No	No	No	No	No	No	No	No	No

SuperHarm Data File - cont

```
//      200 kVAr, 480 Volt 4.7th Harmonic Filter
//      Installed on 480 Volt Bus #2

SERIESFILTER     NAME = FILT2A
                 CAPBUS = 4802A          MIDBUS = REACT2A
                 INDBUS = GROUND
                 KV = 0.277      MVA = 0.0667        HARMONIC = 4.7

SERIESFILTER     NAME = FILT2B
                 CAPBUS = 4802B          MIDBUS = REACT2B
                 INDBUS = GROUND
                 KV = 0.277      MVA = 0.0667        HARMONIC = 4.7

SERIESFILTER     NAME = FILT2C
                 CAPBUS = 4802C          MIDBUS = REACT2C
                 INDBUS = GROUND
                 KV = 0.277      MVA = 0.0667        HARMONIC = 4.7
```