

# Analysis for Solving Harmonics Resonance Problems



# PQ Studies Overview



## Client Base

- Utility
- Industrial/Commercial
- Research & Development

## Practice Areas

- Monitoring Service: [www.powermonitoring.com](http://www.powermonitoring.com)
- PQSoft: [www.pqsoft.com](http://www.pqsoft.com)
- Utility Studies
- Industrial Studies
- Research Projects

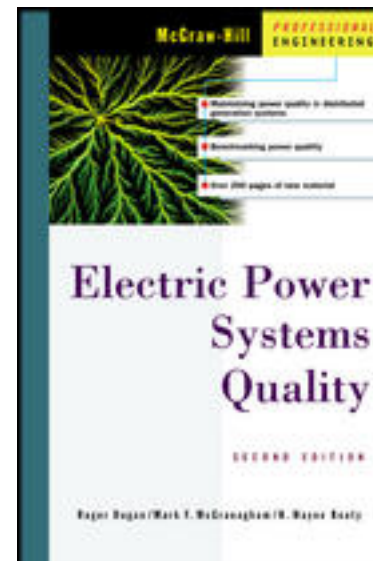
## Expertise

- Monitoring, diagnosing, solving PQ problems
- Simulations (harmonics, transients, voltage sags)
- Power conditioning economic evaluation
- Utility PQ program development
- Seminars and training

# Electrotek is Recognized for our Power Quality Expertise

*We literally “wrote the book” on Power Quality*

*The clearest, most complete reference on an increasingly important - and often complex - topic.*



# Analysis for Solving Harmonics Resonance Problems

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# Topics

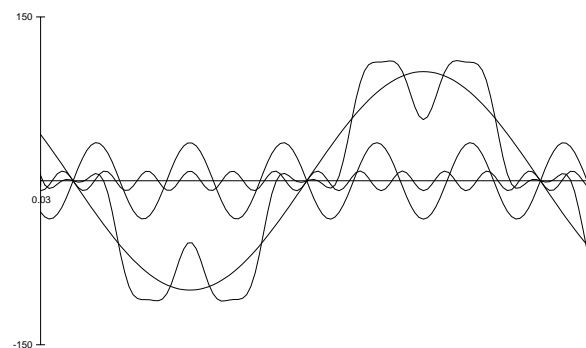
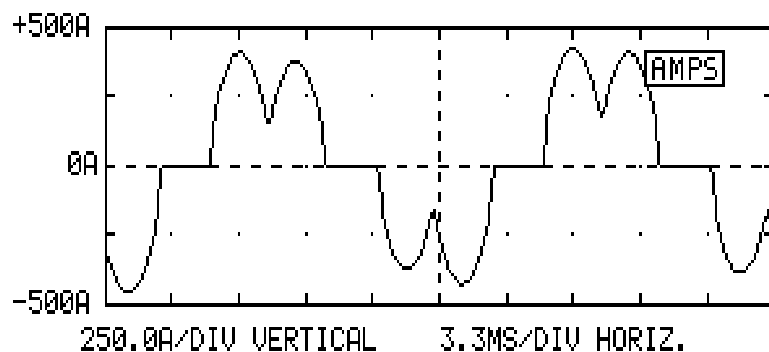
- Introduction
- Basic Harmonic Principles
- IEEE 519
- Example Harmonics Study Using Computer Modeling
- Conclusion

# Question

- How many of you have come across harmonics problems?

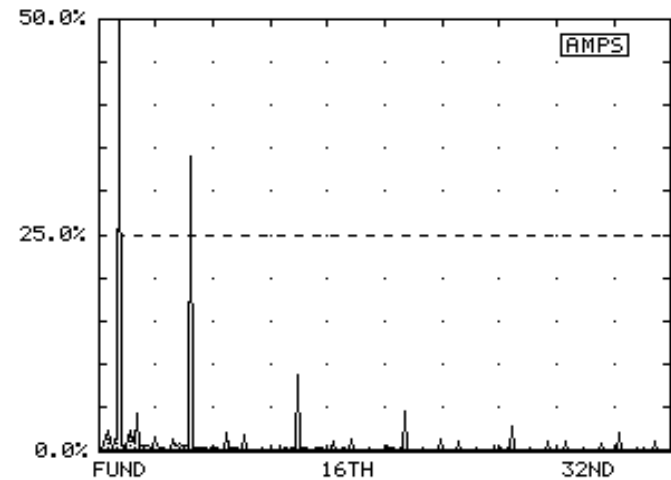
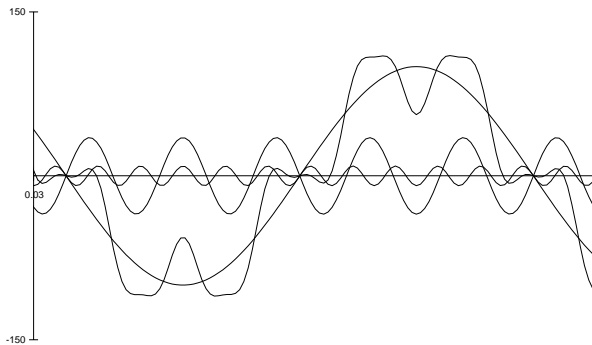
# Harmonics

- Harmonics are persistent distortions in a waveshape
- They represent integer multiples of the fundamental frequencies



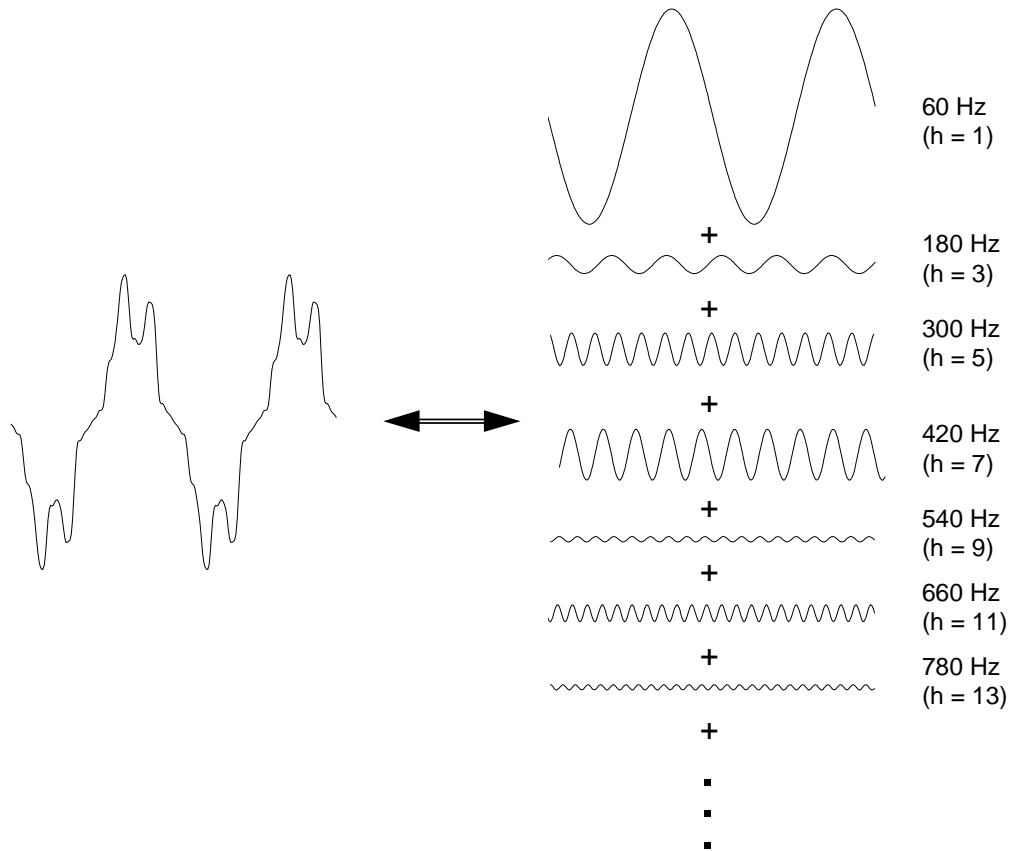
# Harmonic Spectrum Analysis

- Is a “recipe” of the harmonic frequencies present





# Harmonic Components



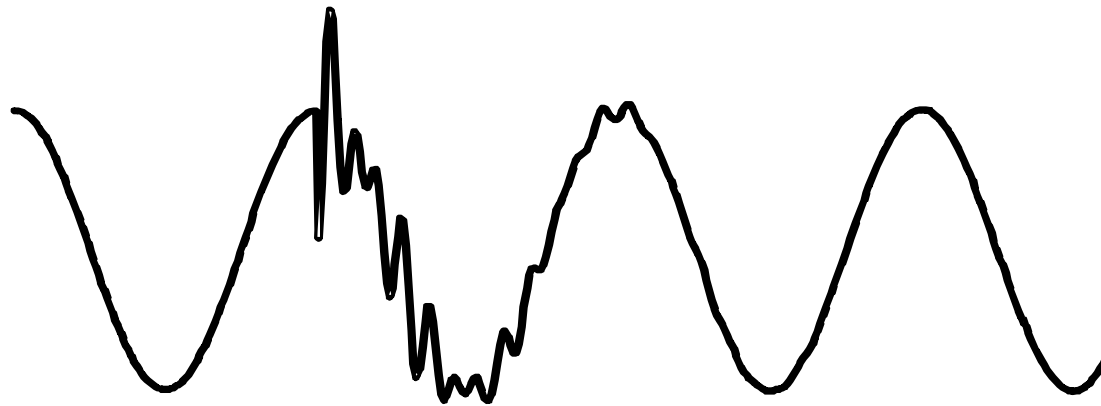
# Effects of Harmonics on Equipment

*In general, harmonics increase heating and losses in almost every piece of equipment in the electric power system.*

- Capacitor banks - usually cause the resonant condition where the highest distortion levels occur
- Resistive loads - will absorb slightly more power
- Motor loads - harmonic fluxes within the motor
- Power transformers - hot spots within the windings
- Electronic controls - operate improperly
- Communication circuits - can cause interference

# Question

- Do you see harmonics in the waveshape below?



# Harmonics vs. Transients

- Harmonics are Steady-State and persistent
  - Frequency components are multiples of a base frequency
- Transients are due to changes in state
  - Frequency components are natural frequencies of the system

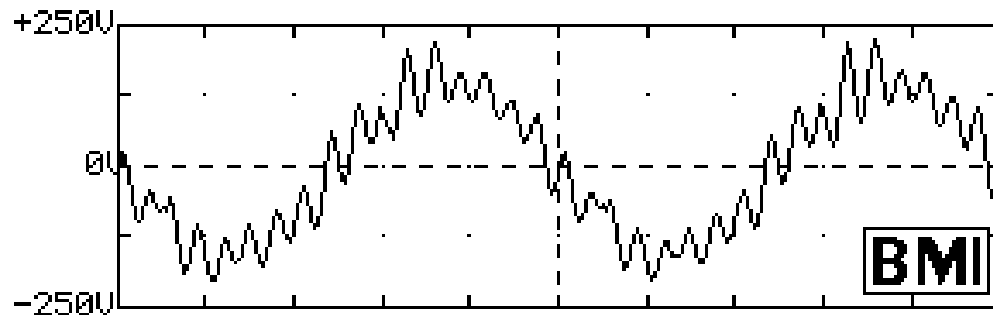
# Harmonics Resonance

TE COPIER Sep 16 1991 (Mon)

PHASE A VOLTAGE SPECTRUM 9:58:25 AM

Fundamental volts: 113.6 Urms

Fundamental freq: 60.0 Hz



PHASE A SNAPSHOT

| HARM | PCT    | SINE PHASE | HARM | PCT  | SINE PHASE |
|------|--------|------------|------|------|------------|
| FUND | 100.0% | 0          | 2nd  | 0.4% | 105        |
| 3rd  | 0.9%   | -160       | 4th  | 0.2% | 54         |
| 5th  | 0.9%   | 70         | 6th  | 0.1% | -43        |
| 7th  | 0.9%   | 117        | 8th  | 0.2% | 117        |
| 9th  | 0.8%   | -179       | 10th | 0.2% | -179       |
| 11th | 0.9%   | -156       | 12th | 0.2% | -147       |
| 13th | 0.4%   | 121        | 14th | 0.4% | -59        |
| 15th | 0.4%   | 135        | 16th | 2.0% | -140       |
| 17th | 24.1%  | -176       | 18th |      |            |
| 19th | 4.1%   | 90         | 20th | 0.2% | -114       |
| 21st | 0.6%   | -77        | 22nd | 0.2% | -135       |
| 23rd | 0.9%   | -56        | 24th | 0.2% | 146        |
| 25th |        |            | 26th |      |            |
| 27th | 0.1%   | -39        | 28th | 0.2% | -109       |
| 29th | 0.4%   | -106       | 30th | 0.1% | 48         |
| 31st | 0.6%   | 147        | 32nd | 0.1% | 21         |
| 33rd | 0.4%   | 159        | 34th | 0.1% | -59        |
| 35th | 0.5%   | 11         | 36th |      |            |
| 37th | 0.6%   | -70        | 38th | 0.2% | -20        |
| 39th | 0.4%   | -89        | 40th |      |            |
| 41st | 1.0%   | 150        | 42nd | 0.1% | 100        |
| 43rd | 0.7%   | 60         | 44th | 0.2% | -29        |
| 45th | 0.4%   | -31        | 46th |      |            |
| 47th | 0.9%   | -84        | 48th |      |            |
| 49th | 0.7%   | -167       | 50th | 0.1% | 86         |
| ODD  | 29.6%  |            | EVEN | 2.2% |            |
| THD: | 29.7%  |            |      |      |            |

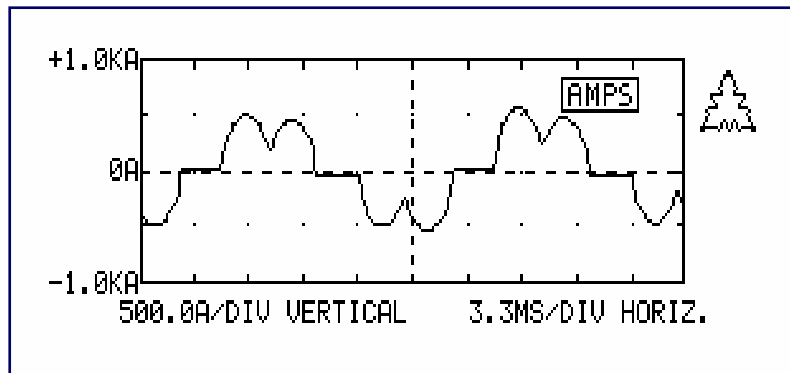
# Question

- What is the IEEE recommended limit for voltage THD?
  - 1%
  - 3%
  - 5%
  - 10%

# 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

# DC Motor Drive Current



VOLTAGE & CURRENT SNAPSHOT 11:21:16 AM

| VOLTAGE    |              | 458.9 Vrms  |  |
|------------|--------------|-------------|--|
| Phase A-B: | 459.3 Vrms,  | 0° (ref)    |  |
| Phase B-C: | 461.0 Vrms,  | 120°        |  |
| Phase C-A: | 456.5 Vrms,  | -121°       |  |
| Imbalance: | 0.4%         |             |  |
| CURRENT    |              | 945.6 A rms |  |
| Phase A:   | 339.5 A rms, | -75°        |  |
| Phase B:   | 347.8 A rms, | 40°         |  |
| Phase C:   | 258.3 A rms, | 157°        |  |
| Imbalance: | 9.4%         |             |  |

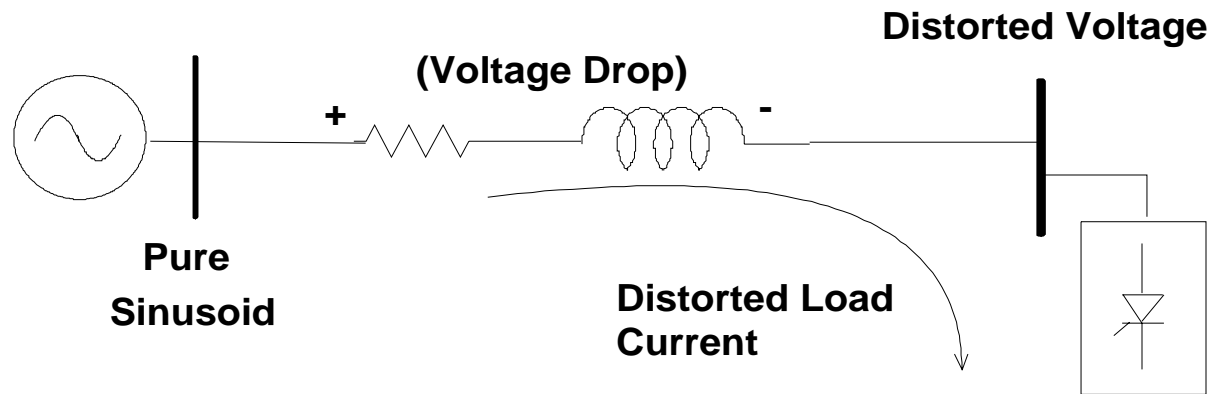
PHASE A CURRENT SPECTRUM 11:20:42 AM

Fundamental amps: 319.6 A rms  
Fundamental freq: 60.0 Hz

| HARM | PCT    | PHASE | HARM | PCT  | PHASE |
|------|--------|-------|------|------|-------|
| FUND | 100.0% | -75°  | 2nd  | 4.8% | -64°  |
| 3rd  | 1.2%   | 28°   | 4th  | 1.5% | 164°  |
| 5th  | 33.6%  | 156°  | 6th  |      |       |
| 7th  | 1.6%   | 29°   | 8th  | 1.7% | -170° |
| 9th  | 0.4%   | -91°  | 10th | 0.3% | 96°   |
| 11th | 8.7%   | 49°   | 12th |      |       |
| 13th | 1.2%   | 54°   | 14th | 1.3% | 86°   |
| 15th | 0.3%   | 148°  | 16th | 0.2% | 51°   |
| 17th | 4.5%   | -57°  | 18th |      |       |
| 19th | 1.3%   | -46°  | 20th | 1.1% | -18°  |
| 21st | 0.3%   | 34°   | 22nd | 0.3% | -31°  |
| 23rd | 2.8%   | -163° | 24th |      |       |
| 25th | 1.2%   | -149° | 26th | 0.9% | -123° |
| 27th | 0.3%   | -75°  | 28th | 0.3% | -128° |
| 29th | 2.0%   | 90°   | 30th |      |       |
| 31st | 1.0%   | 107°  | 32nd | 0.8% | 133°  |
| 33rd | 0.3%   | 173°  | 34th | 0.3% | 135°  |
| 35th | 1.4%   | -17°  | 36th |      |       |
| 37th | 1.0%   | 2°    | 38th | 0.8% | 28°   |
| 39th | 0.3%   | 63°   | 40th | 0.3% | 31°   |
| 41st | 1.1%   | -123° | 42nd |      |       |
| 43rd | 0.9%   | -104° | 44th | 0.8% | -75°  |
| 45th | 0.3%   | -47°  | 46th | 0.3% | -70°  |
| 47th | 1.0%   | 128°  | 48th | 0.2% | 102°  |
| 49th | 0.9%   | 152°  | 50th | 0.7% | -179° |
| ODD  | 35.4%  |       | EVEN | 5.9% |       |
| THD: | 35.9%  |       |      |      |       |



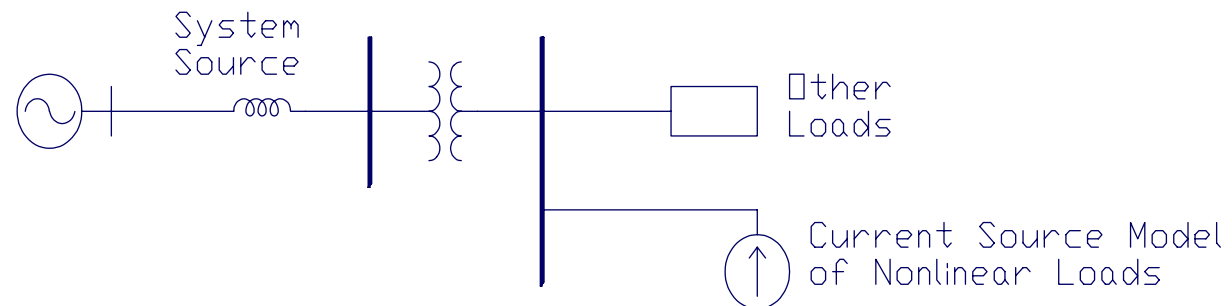
# Current vs. Voltage Harmonics



**Harmonic currents flowing through the system impedance results in harmonic voltages at the load**

# IEEE 519

- Harmonics generated by nonlinear device characteristics
- Most devices look like sources of harmonic currents
- Voltage distortion caused by system response characteristics



# Limits on Harmonic Levels

- The customer is responsible for limiting harmonic currents injected onto the power system.
- The utility is responsible for maintaining quality of voltage waveform.



# Harmonic Voltage Limits

## Utility Responsibility

| <b>Bus Voltage</b>      | <b>Maximum Individual Harmonic Component (%)</b> | <b>Maximum THD (%)</b> |
|-------------------------|--|------------------------|
| <b>69 kV and below</b>  | <b>3.0%</b>                                      | <b>5.0%</b>            |
| <b>115 kV to 161 kV</b> | <b>1.5%</b>                                      | <b>2.5%</b>            |
| <b>Above 161 kV</b>     | <b>1.0%</b>                                      | <b>1.5%</b>            |

# Harmonic Current Limits

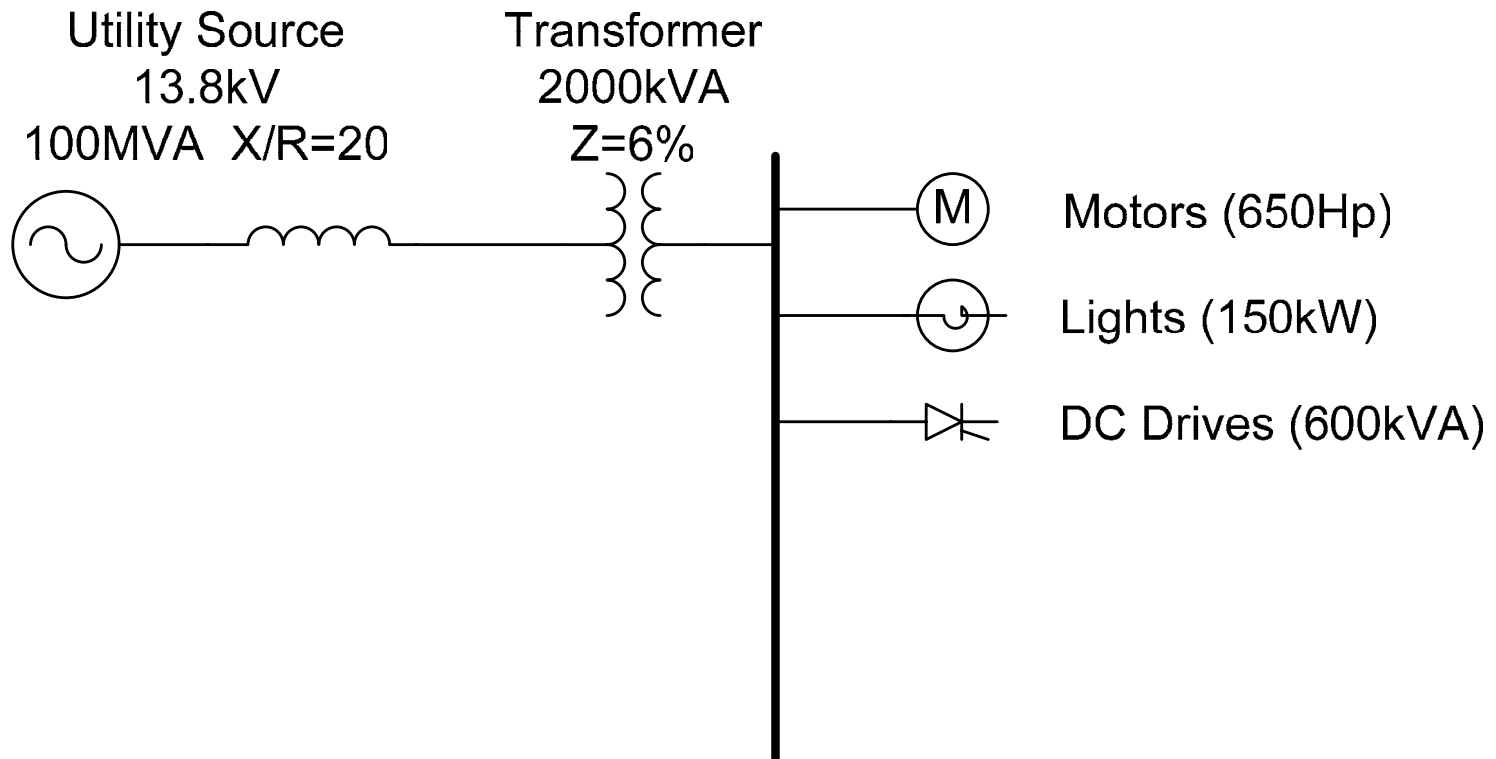
## Customer Responsibility

| $SCR = I_{sc}/I_L$ | <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 |

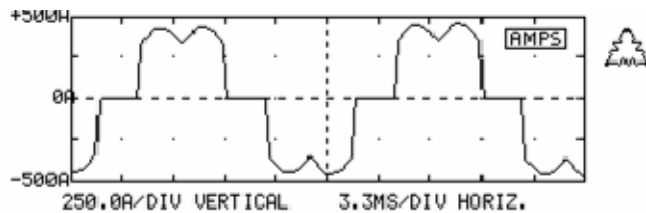
Values shown are in percent of “average maximum demand load current”

SCR = short circuit ration (utility short circuit current at point of common coupling divided by customer average maximum demand load current)

# Plastics Plant One-Line



# Typical DC Drive Current



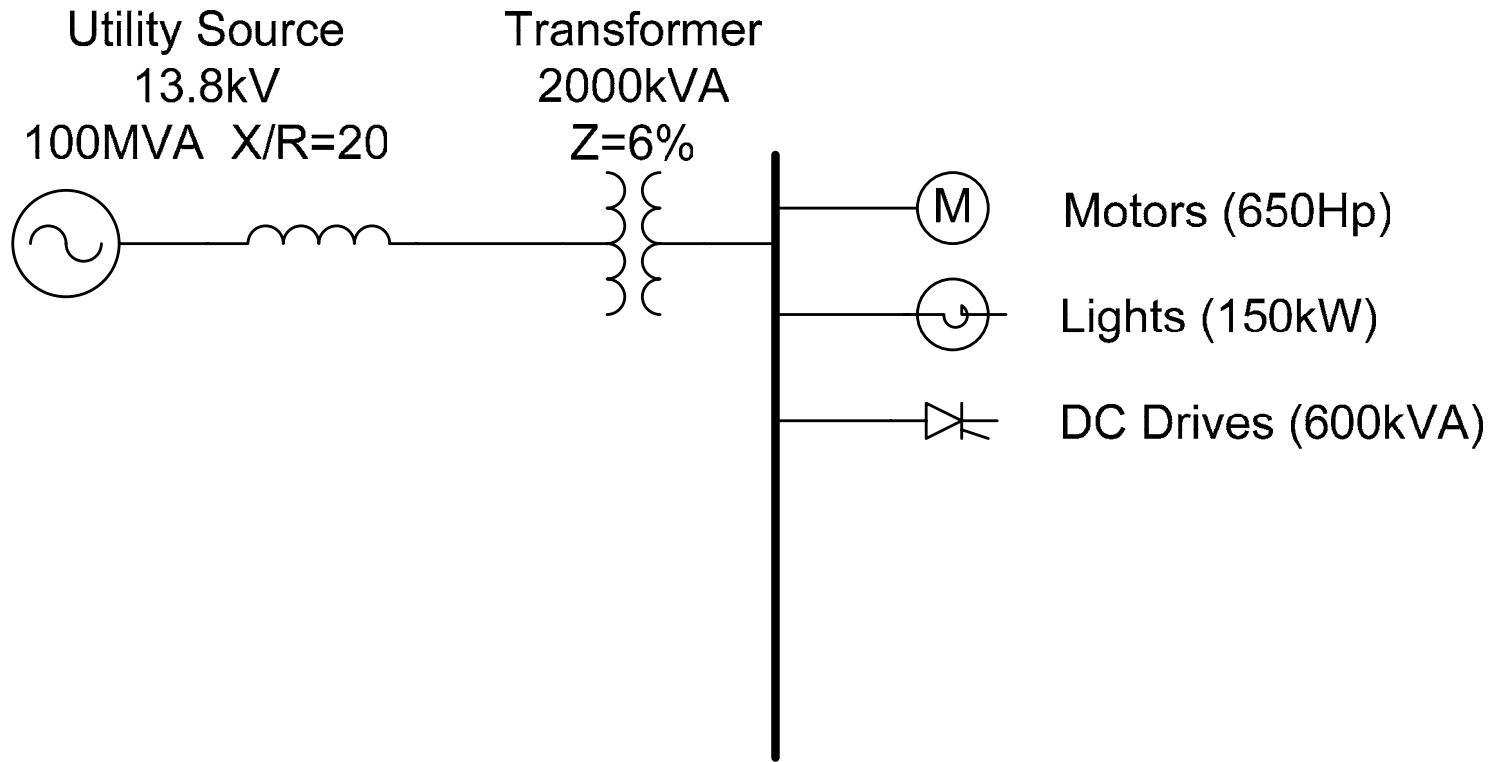
PHASE A CURRENT SPECTRUM 10:49:13 AM

Fundamental amps: 323.6 A rms

Fundamental freq: 59.9 Hz

| HARM | PCT    | SINE PHASE | HARM | PCT  | SINE PHASE |
|------|--------|------------|------|------|------------|
| FUND | 100.0% | -33        | 2nd  | 0.2% | 1          |
| 3rd  | 0.9%   | -17        | 4th  |      |            |
| 5th  | 24.8%  | 14         | 6th  |      |            |
| 7th  | 0.3%   | -56        | 8th  |      |            |
| 9th  | 0.3%   | -99        | 10th |      |            |
| 11th | 0.3%   | -10        | 12th |      |            |
| 13th | 5.4%   | -74        | 14th |      |            |
| 15th | 0.3%   | -114       | 16th |      |            |
| 17th | 4.5%   | -28        | 18th |      |            |
| 19th | 4.1%   | -98        | 20th |      |            |
| 21st | 0.4%   | -147       | 22nd |      |            |
| 23rd | 3.4%   | -48        | 24th |      |            |
| 25th | 3.0%   | -118       | 26th |      |            |
| 27th | 0.3%   | -174       | 28th |      |            |
| 29th | 2.5%   | -69        | 30th |      |            |
| 31st | 2.4%   | -138       | 32nd |      |            |
| 33rd | 0.3%   | 167        | 34th |      |            |
| 35th | 1.9%   | -90        | 36th |      |            |
| 37th | 1.9%   | -156       | 38th |      |            |
| 39th | 0.2%   | 154        | 40th |      |            |
| 41st | 1.6%   | -108       | 42nd |      |            |
| 43rd | 1.6%   | -174       | 44th |      |            |
| 45th | 0.2%   | 144        | 46th |      |            |
| 47th | 1.3%   | -128       | 48th |      |            |
| 49th | 1.3%   | 171        | 50th |      |            |
| ODD  | 29.5%  |            | EVEN | 0.2% |            |
| THD: | 29.2%  |            |      |      |            |

# Plastics Plant Case Study



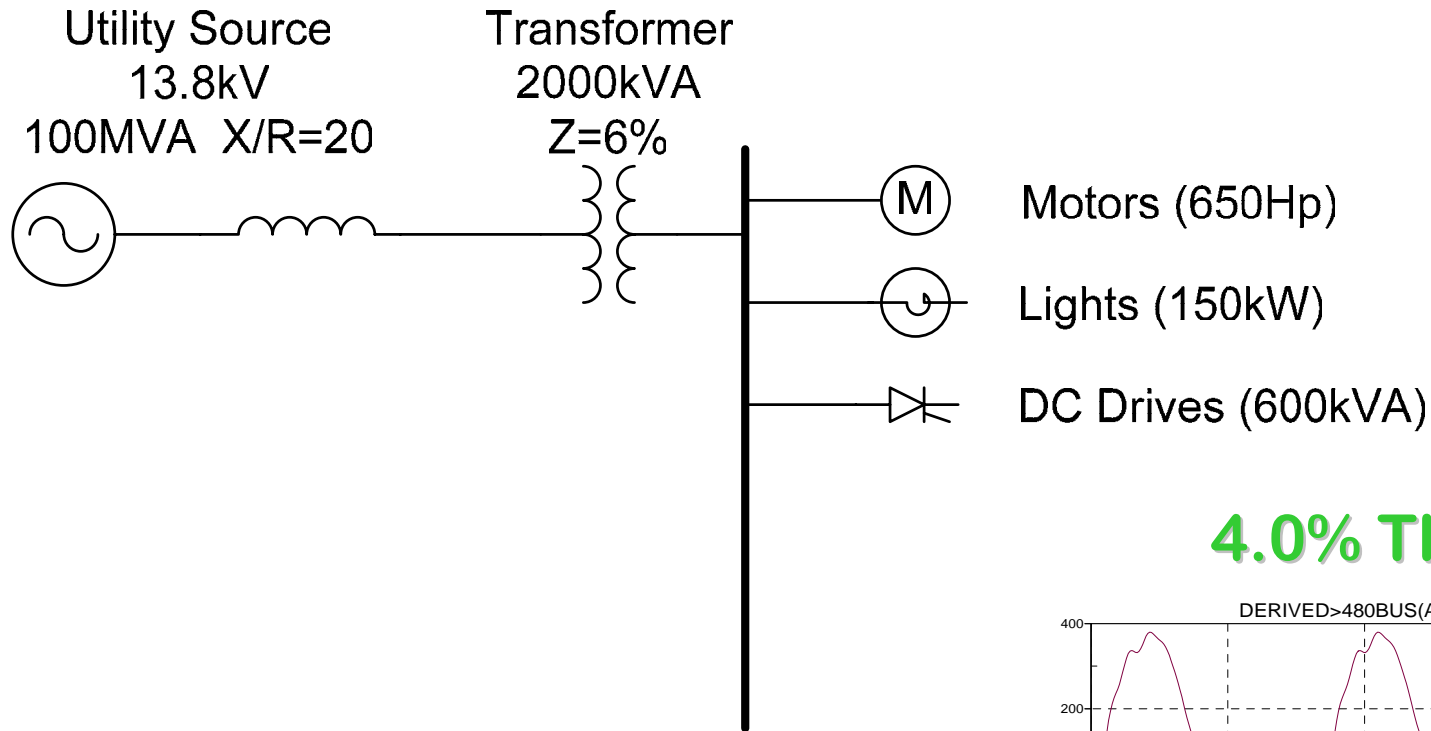
**Do you expect harmonic problems from this configuration?**



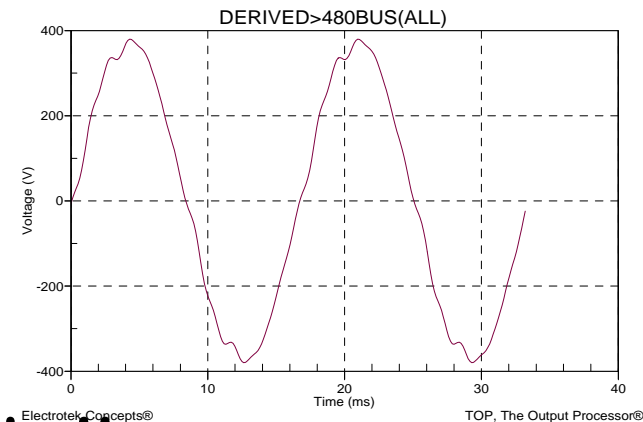
# Questions

- Do you expect harmonic problems from this configuration?
  - Yes
  - No

# Before PF Correction



**4.0% THD**



**Actually this situation is acceptable !!**

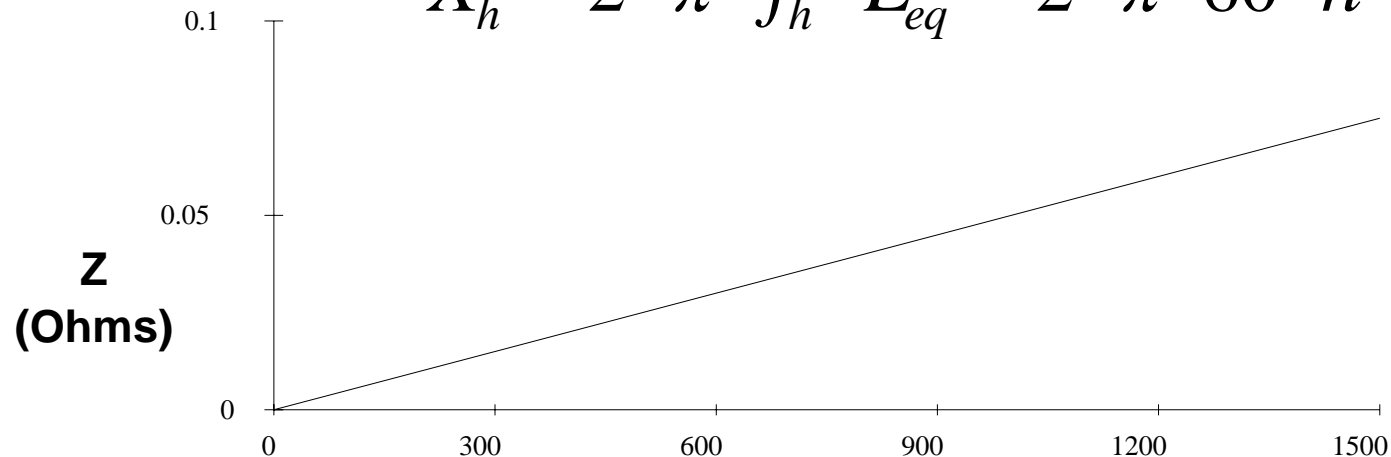
# Impedance Vs. Frequency

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

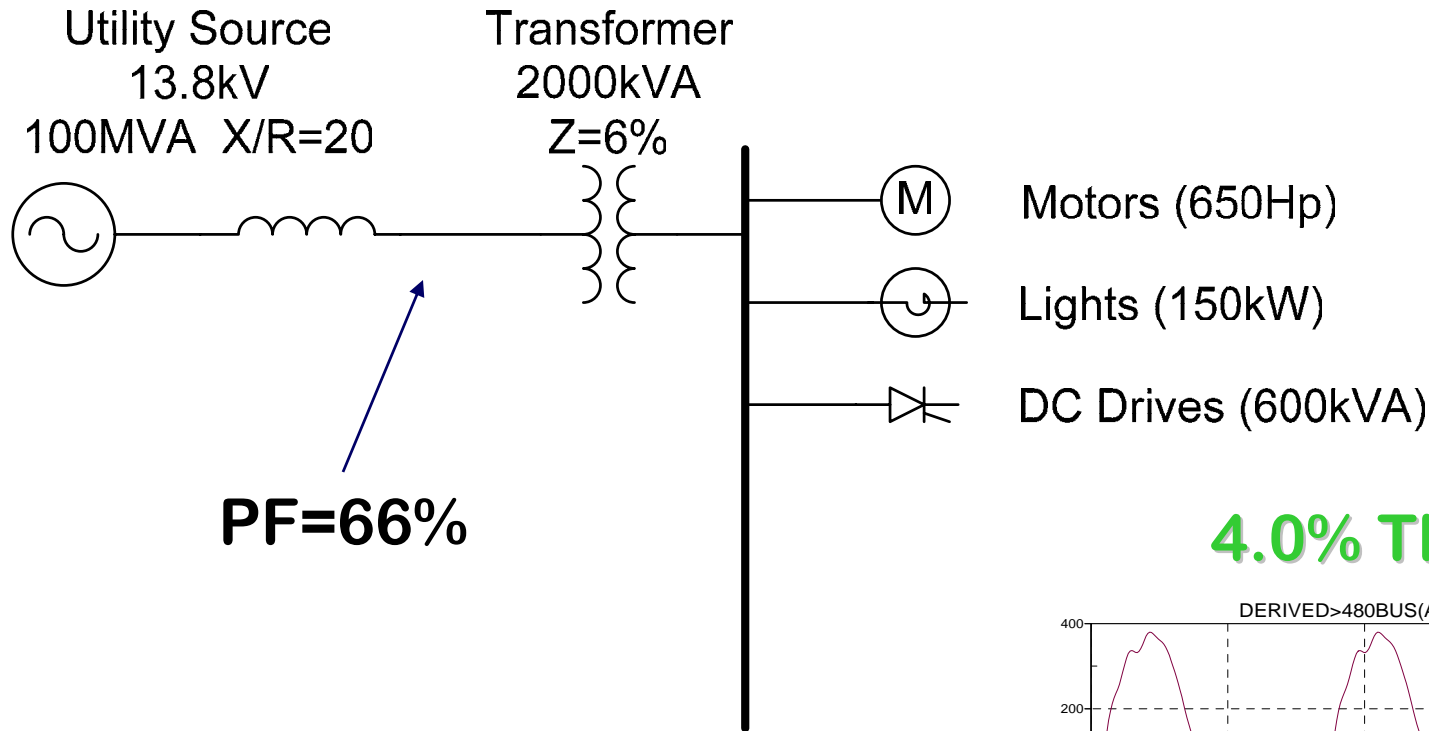
**h** = harmonic number

**f<sub>h</sub>** = harmonic frequency

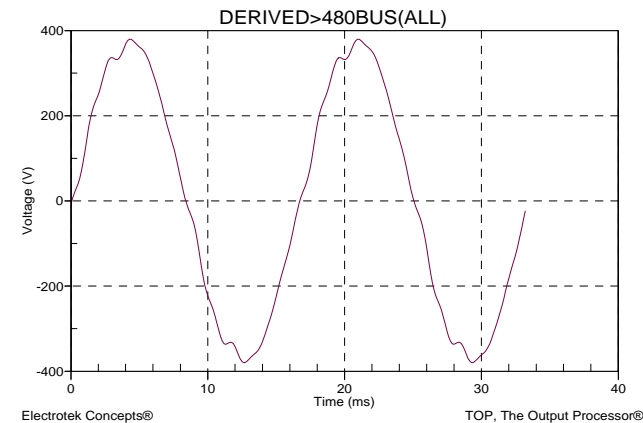
$$X_h = 2 \cdot \pi \cdot f_h \cdot L_{eq} = 2 \cdot \pi \cdot 60 \cdot h \cdot L_{eq}$$



# Before PF Correction

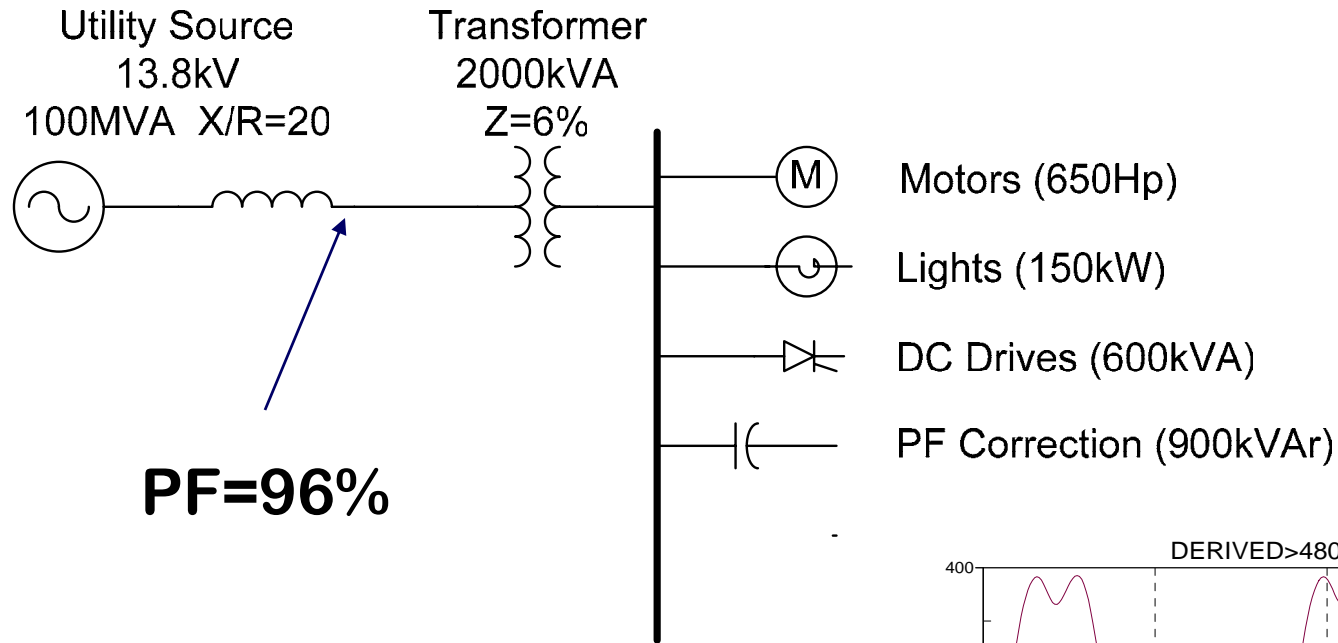


4.0% THD

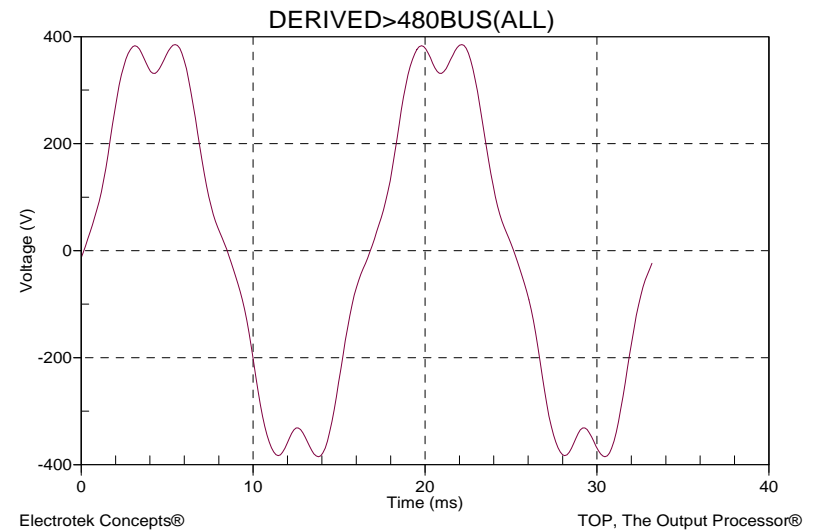


But power factor is low.....

# Add PF Correction

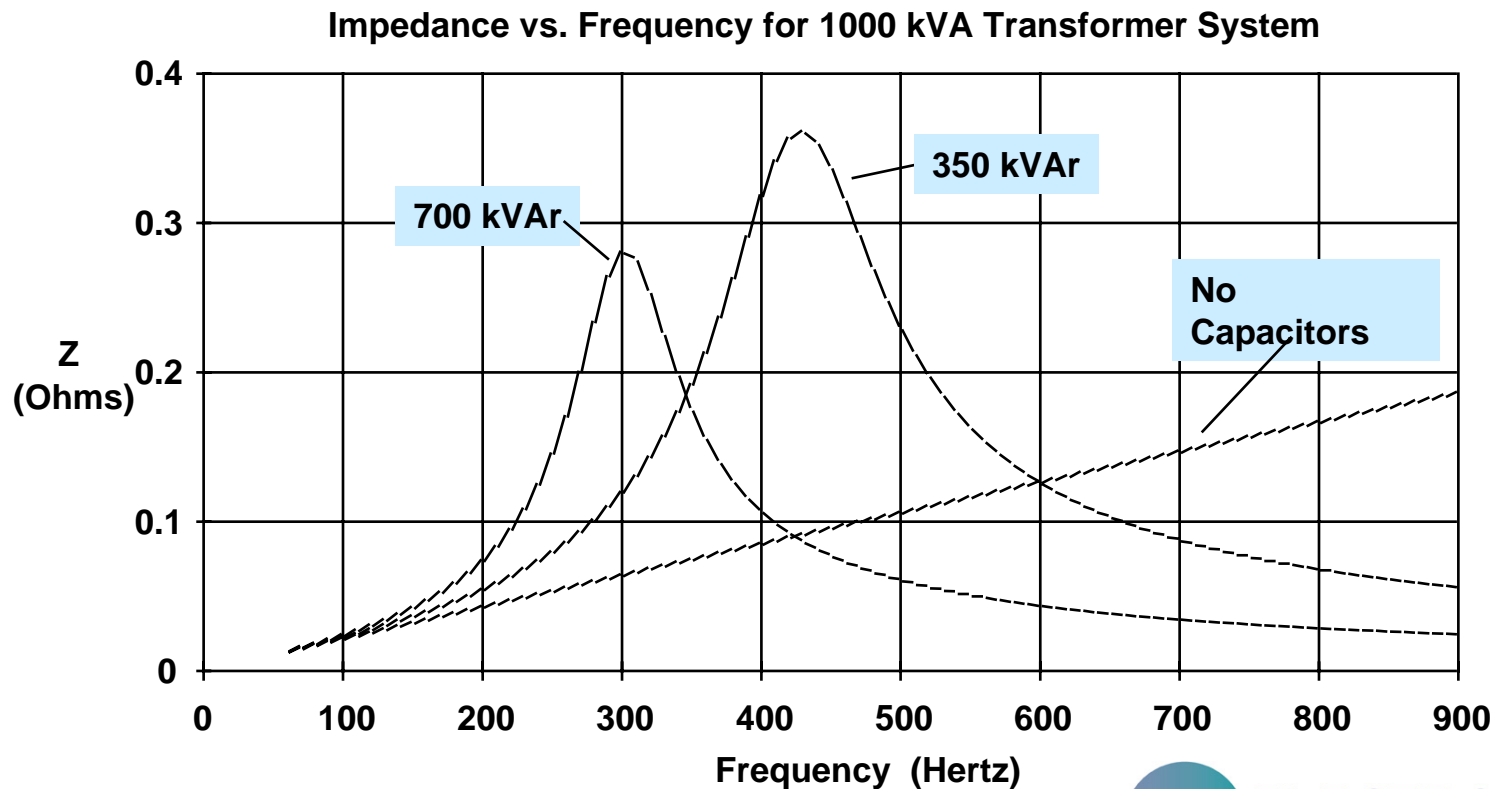


**12.2% THD**

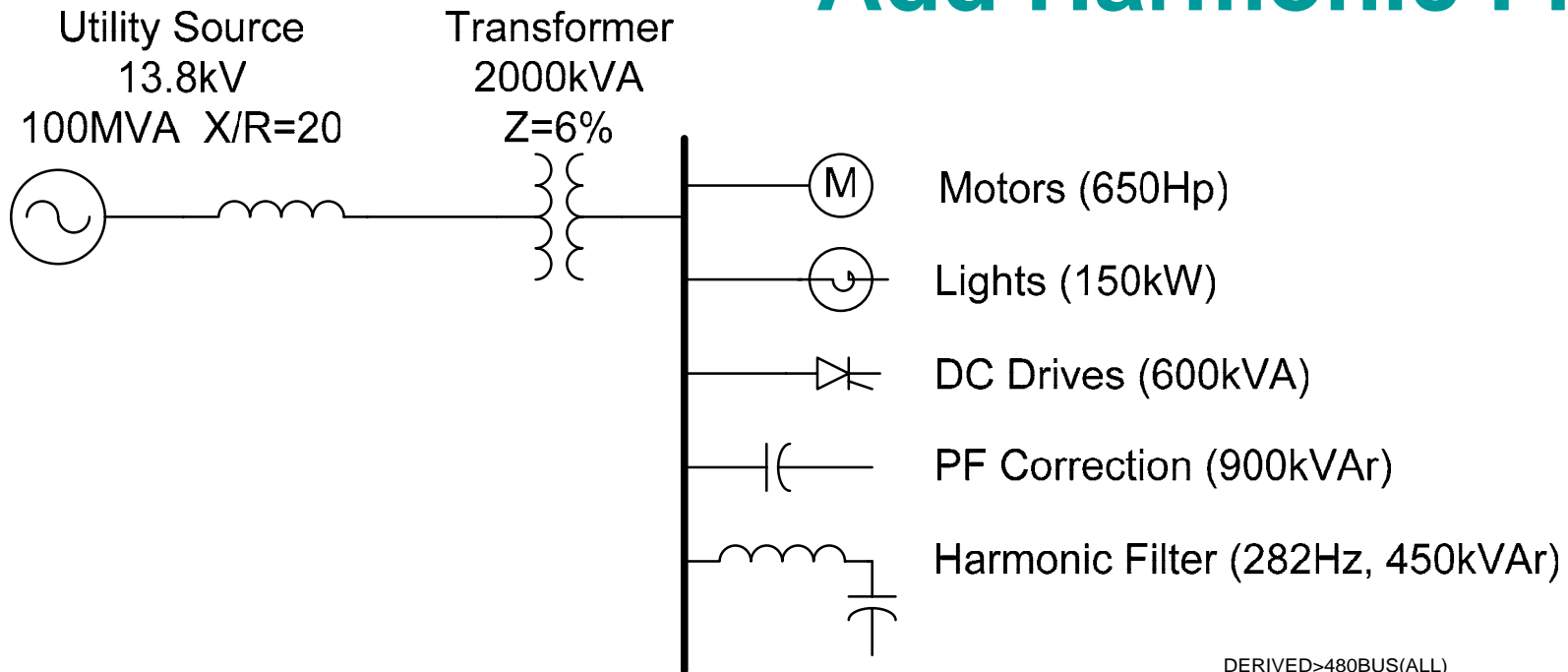


# Effect of Power Factor Correction

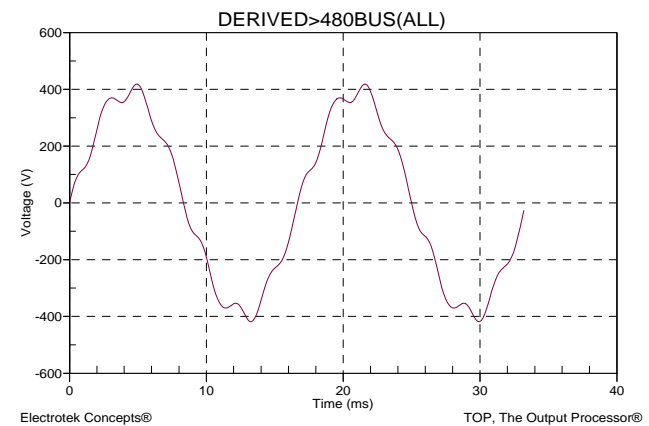
- Shunt capacitors can dramatically alter the system frequency response.



# Add Harmonic Filter

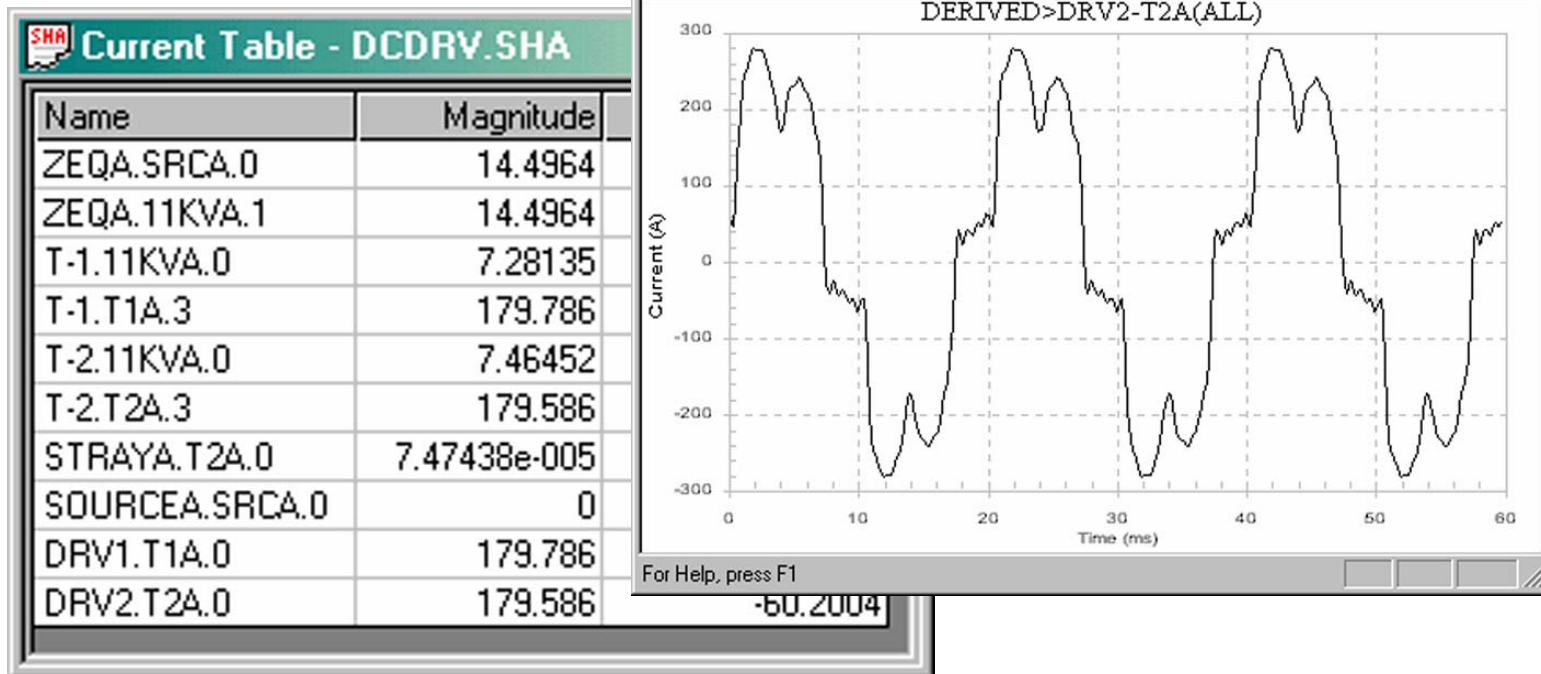


**8.5% THD**



# SuperHarm

*Developed by Electrotek, a widely-used software for simulation and analysis of harmonics on power systems*





# Harmonic Analysis

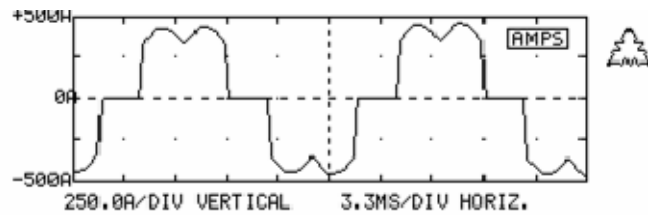
- Build a model of the system of interest
- Determine harmonic source characteristics
- Run simulations
- Examine results
- Design solutions
- Check solutions

# Measured Drive Current

PHASE A CURRENT SPECTRUM 10:49:13 AM

Fundamental amps: 323.6 A rms

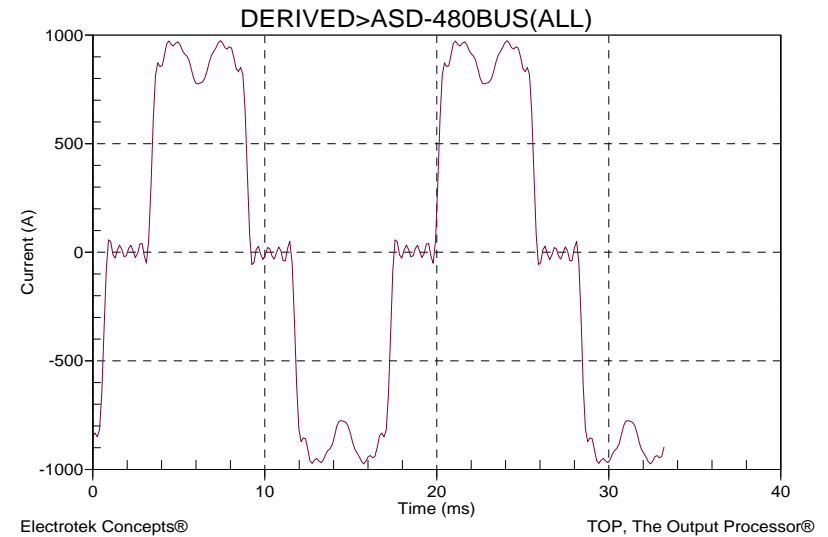
Fundamental freq: 59.9 Hz



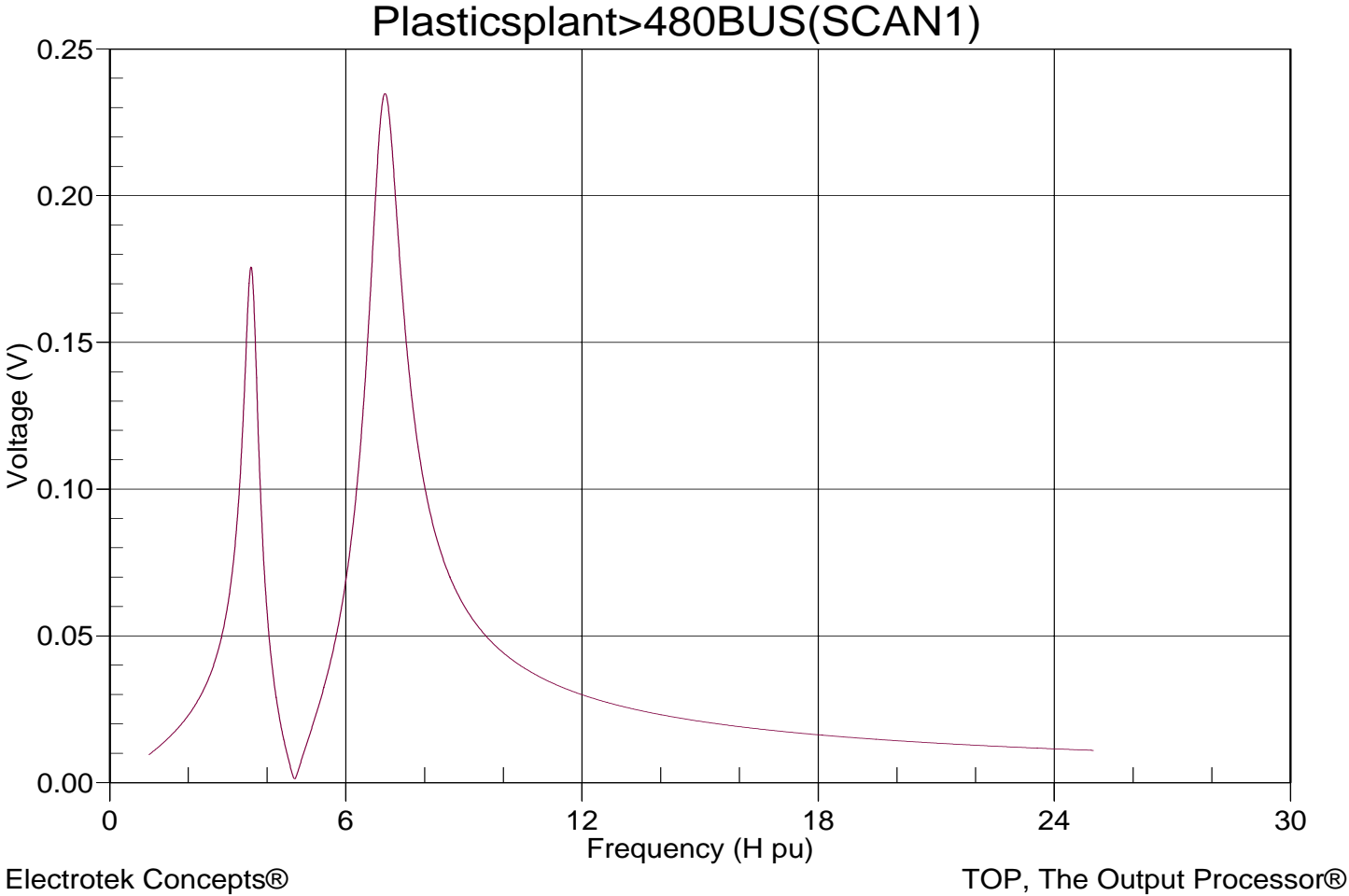
| HARM | PCT    | SINE PHASE | HARM | PCT  | SINE PHASE |
|------|--------|------------|------|------|------------|
| FUND | 100.0% | -33        | 2nd  | 0.2% | 1          |
| 3rd  | 0.9%   | -17        | 4th  |      |            |
| 5th  | 24.8%  | 14         | 6th  |      |            |
| 7th  | 0.3%   | -56        | 8th  |      |            |
| 9th  | 0.3%   | -99        | 10th |      |            |
| 11th | 0.3%   | -10        | 12th |      |            |
| 13th | 5.4%   | -74        | 14th |      |            |
| 15th | 0.3%   | -114       | 16th |      |            |
| 17th | 4.5%   | -28        | 18th |      |            |
| 19th | 4.1%   | -98        | 20th |      |            |
| 21st | 0.4%   | -147       | 22nd |      |            |
| 23rd | 3.4%   | -48        | 24th |      |            |
| 25th | 3.0%   | -118       | 26th |      |            |
| 27th | 0.3%   | -174       | 28th |      |            |
| 29th | 2.5%   | -69        | 30th |      |            |
| 31st | 2.4%   | -138       | 32nd |      |            |
| 33rd | 0.3%   | 167        | 34th |      |            |
| 35th | 1.9%   | -90        | 36th |      |            |
| 37th | 1.9%   | -156       | 38th |      |            |
| 39th | 0.2%   | 154        | 40th |      |            |
| 41st | 1.6%   | -108       | 42nd |      |            |
| 43rd | 1.6%   | -174       | 44th |      |            |
| 45th | 0.2%   | 144        | 46th |      |            |
| 47th | 1.3%   | -128       | 48th |      |            |
| 49th | 1.3%   | 171        | 50th |      |            |
| ODD  | 29.5%  |            | EVEN | 0.2% |            |
| THD: | 29.2%  |            |      |      |            |

# Simulated Harmonic Source

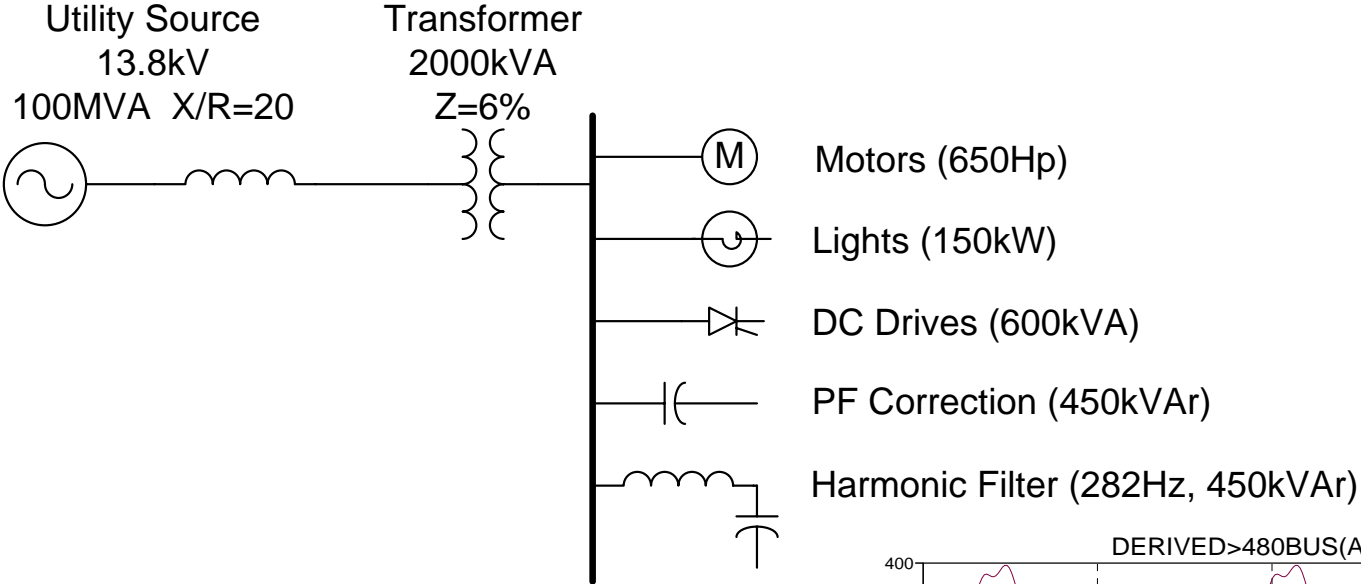
```
NONLINEARLOAD NAME = ASD
  BUS = 480BUS
  KV = 0.277   KVA =200.0
  DF = 0.75
  TABLE = {
    { 1, 100.0, -33.0},
    { 5, 24.8, 14.0},
    { 7, 8.3, -56.0},
    {11, 8.3, -10.0},
    {13, 5.4, -74.0},
    {17, 4.5, -28.0},
    {19, 4.1, -98.0},
    {23, 3.4, -48.0},
    {25, 3.0, -118.0}
  }
```



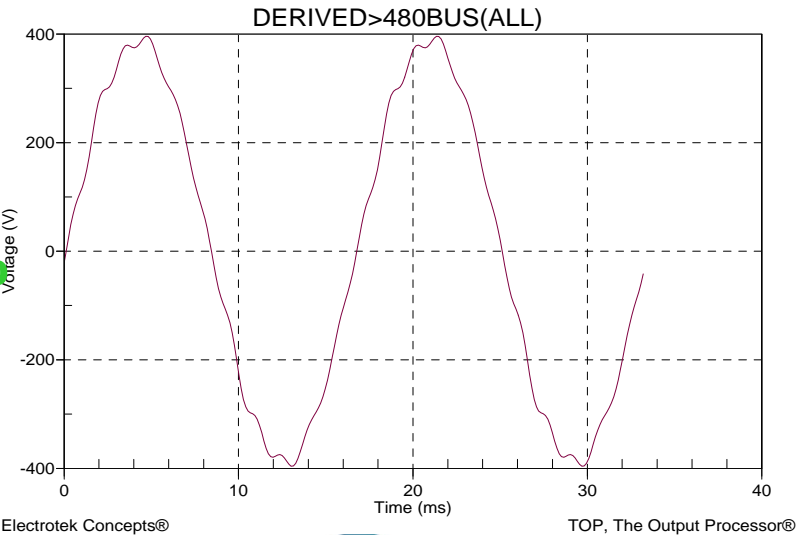
# Resonance with Filter and 900kVAr Capacitor



# Add Harmonic Filter, Reduce PF Corr

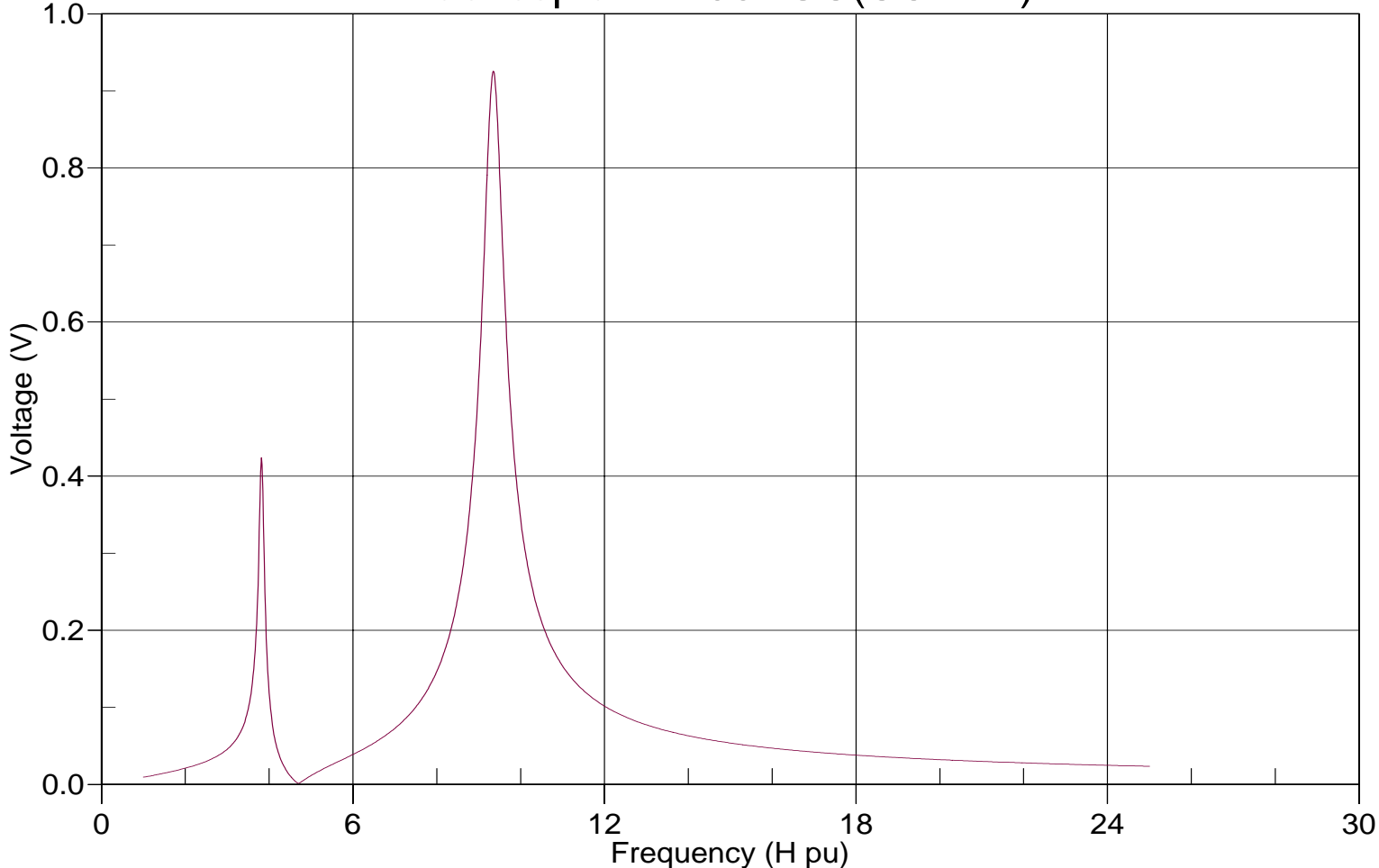


**THD=3.7%**



# Resonance with Filter and 450kVAr Capacitor

Plasticsplant>480BUS(SCAN1)

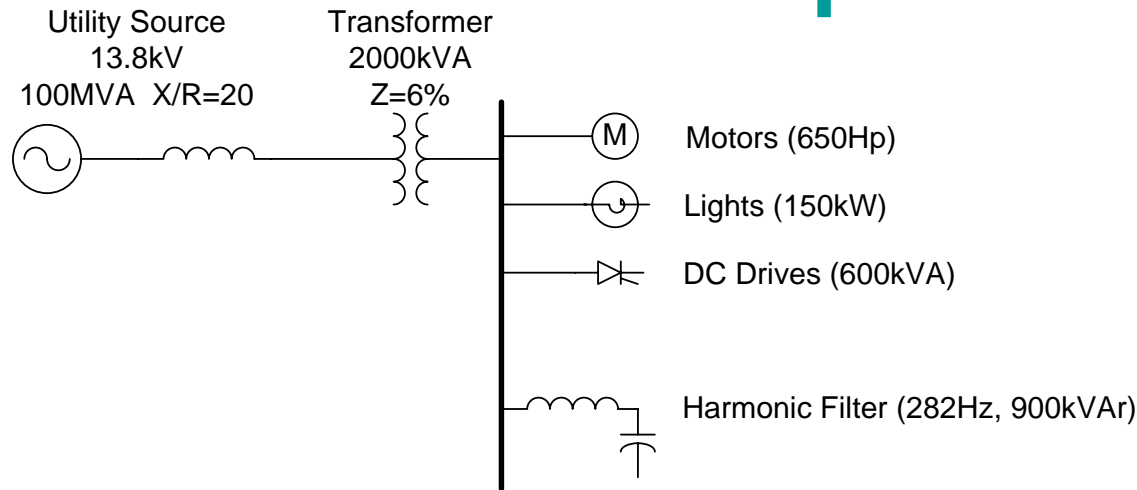


Electrotek Concepts®

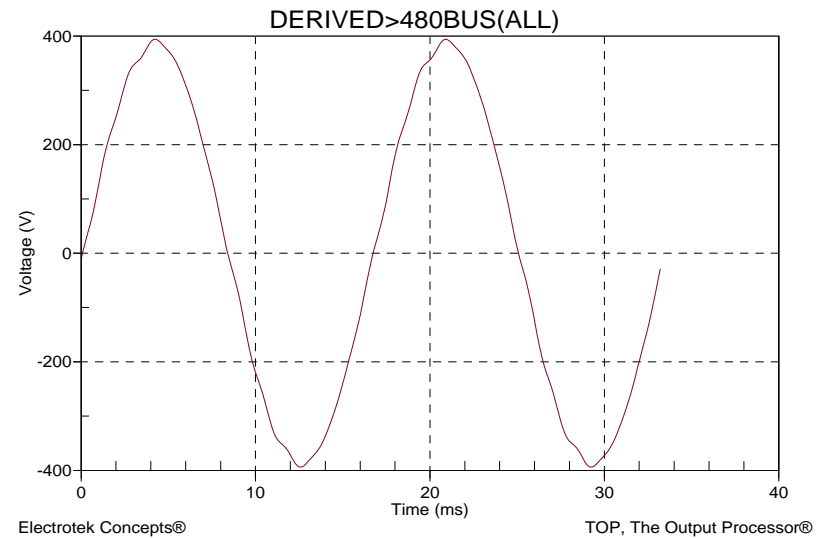
TOP, The Output Processor®



# Proper 900kVAr Filter

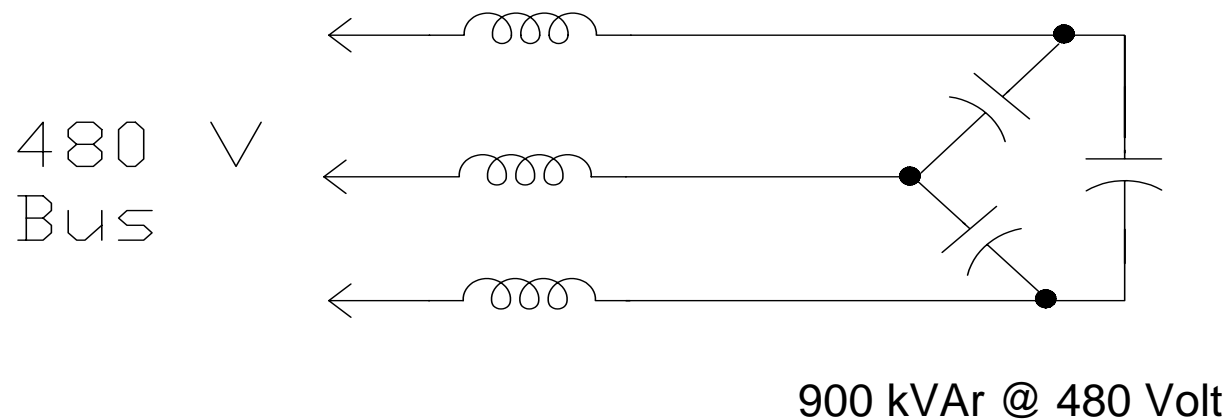


**THD=1.5%**



# Final Solution

- In general, it is best to apply the filter at or below the lowest harmonic of concern.
- The filter connections are shown below:





# What We Have Learned

- Harmonics are persistent distortions in a waveshape
- Power electronics are a prime source of harmonics
- Power factor capacitors aggravate harmonic problems
- Modeling and simulations can evaluate various solution alternatives

# Contact Information

- Visit our website at [www.electrotek.com](http://www.electrotek.com)
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