ECE 528 – Understanding Power Quality

http://www.ece.uidaho.edu/ee/power/ECE528/

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Lecture 2

Today…

- Some homework suggestions
- Power Factor and power factor correction
- The multi-frequency power system
- Frequency’s impact on the power system
- Accidental apparatus
- Finding the frequencies
- “Signature” waveforms

Some homework suggestions:

- Document your work - see grading summary
- Use appropriate units
- When possible, check your answer
  - Solve the problem another way
  - Work the problem backwards

Some homework suggestions:
Working with variables and units in Mathcad-Prime

Define Variables with units: ***(Most units we'll need are built-in.)***

$Cap := 20\mu F \quad f := 60Hz$

Enter equations using defined variables:

$$X_c := \frac{1}{2 \cdot \pi \cdot f \cdot Cap}$$

Then let Prime solve it:

$$X_c = 132.629\,\Omega$$

Compare the work above to this:

$$\frac{1}{376.991 \cdot 20 \cdot 10^{-6}} = 132.629$$

The answers are the same, but the answer on the left must be manually transcribed to other portions of the calculation, and if an error was made, it would be difficult to trace.

Power Factor and Power Factor Correction

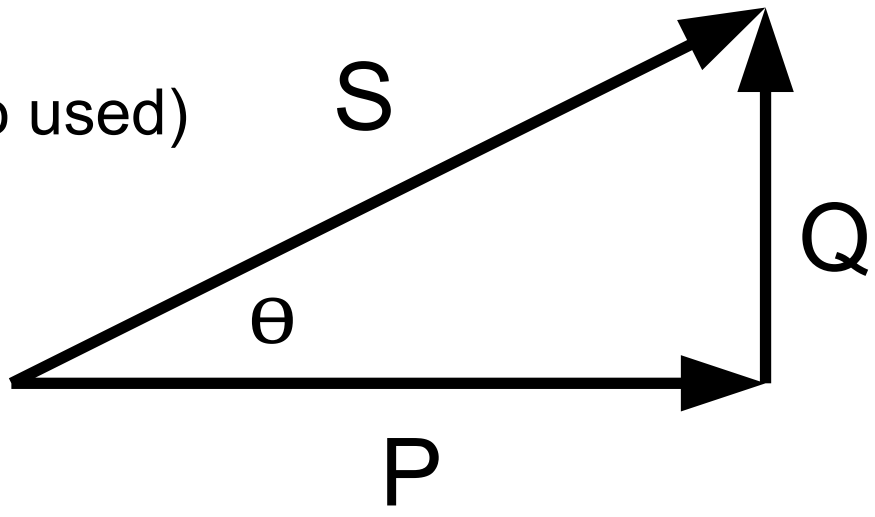
- Poor power factor can be a steady-state power quality problem.
  - Increases heating in transformers and conductors and increases system losses (I^2R)
  - Increases voltage drop through the system
  - Reduces available system capacity
- PQ engineers may be called on to assist customers with sizing power factor correction capacitors.
- Power factor correction capacitors, or “caps” as utility engineers may call them, provide reactive power, or considered another way, consume negative reactive power.
- More information on the class website:
  - *Eaton’s “Power Factor Correction: a guide for the plant engineer”*
  - *Power Factor Teaching Tool – an Excel Workbook to illustrate power factor concepts*
  - *PQ Teaching Toy – a program you can download with visualizations of some important PQ concepts, including power factor*

Power Factor Correction

- Large customers are often subject to a “power factor adjustment” in their electric bill for having a low power factor.
- Example: A customer has a balanced 2MW load operating at 480V (3-phase, line-to-line) at a lagging power factor of 80%. The customer wants to correct the power factor to 90% or better.

The reactive power drawn by the load

P = Real power; Watts (W), kilowatts (kW)
S = Apparent power; Volt-Amps (VA), kilovolt-Amps (kVA)
Q = Reactive Power; Volt-Amps Reactive (VAR), kilovolt-Amps reactive (kVAR) (var, VAr, are also used)

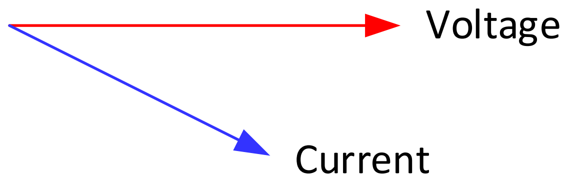


$$pf = \frac{P}{S} \qquad pf = cos(\theta)$$

$$P := 2\ \mathbf{MW} \qquad pf := 0.8$$

$$Q := P \cdot \tan(\mathrm{acos}(pf)) = (1.5 \cdot 10^3)\ \mathbf{kVAR}$$

Note – here we're looking at "displacement" power factor (PF). The voltage and current phasors are displaced from each other. Later we'll look at "distortion PF" and "True PF".



Required size of the capacitor bank

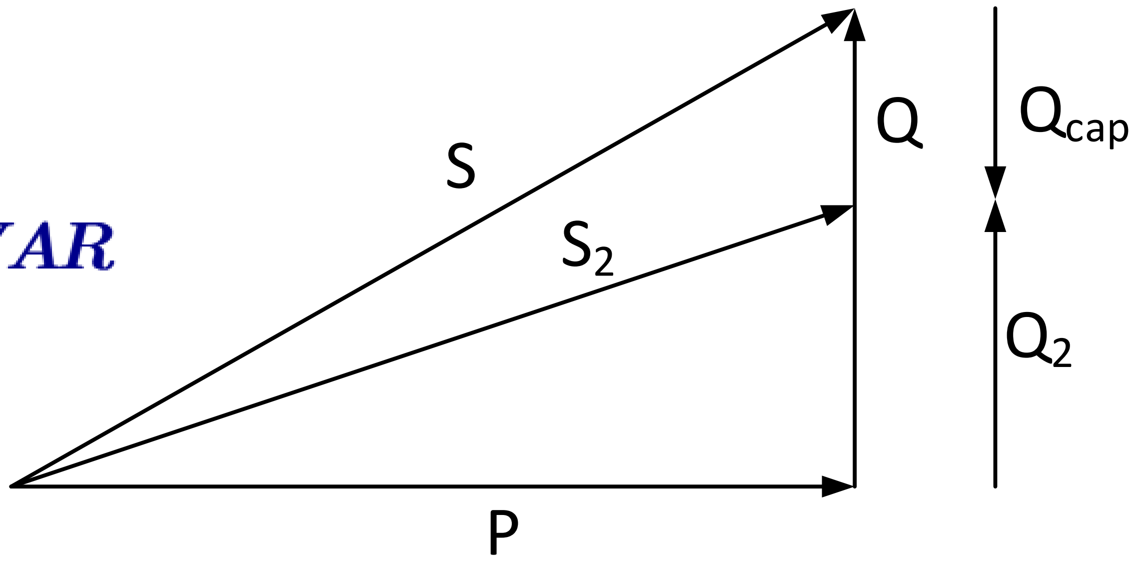
- First, calculate the <u>remaining</u> reactive power requirement:

  $$Q_2 := P \cdot \tan(\operatorname{acos}(0.9)) = 968.644\ kVAR$$

- Correction = initial VAR need – final VAR need:

  $$Q - Q_2 = 531.356\ kVAR$$

- Let us say the customer installs a 600kVAR capacitor.



Corrected power factor

- With the 600kVAR capacitor:

$$Q_{cap} := 600\ \boldsymbol{kVAR} \qquad Q - Q_{cap} = 900\ \boldsymbol{kVAR}$$

$$PF := \cos\left(\operatorname{atan}\left(\frac{Q - Q_{cap}}{P}\right)\right) = 91.192\%$$

600kVAr will improve the power factor to 90% or better.

Reduction in current from the 480V 3-phase source

- Load current without capacitors:

$$S := \frac{P}{pf} = 2.5\ \boldsymbol{MVA}$$

$$I_1 := \frac{S}{\sqrt{3} \cdot 480\ \boldsymbol{V}} = \left(3.007 \cdot 10^3\right)\ \boldsymbol{A}$$

Reduction in current from the 480V 3-phase source

- Load current with capacitors

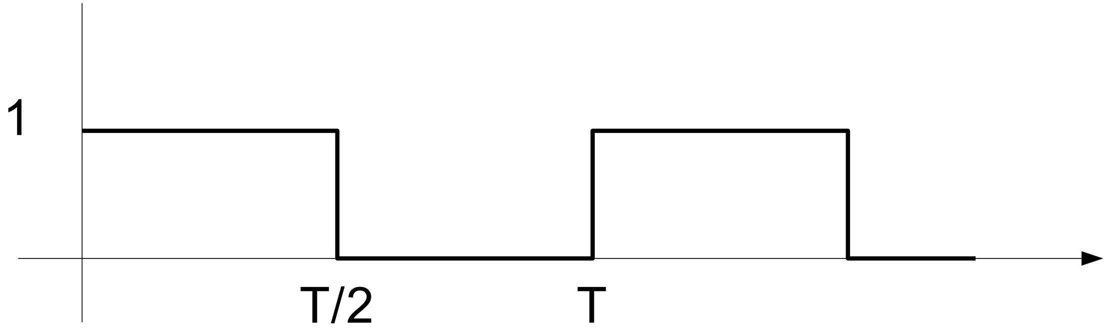
$$S_2 := \frac{P}{PF} = 2.193\ \mathbf{MVA}$$

$$I_2 := \frac{S_2}{\sqrt{3} \cdot 480\ \mathbf{V}} = \left(2.638 \cdot 10^3\right)\ \mathbf{A}$$

$$I_1 - I_2 = 369.058\ \mathbf{A}$$

The Multi-frequency power system

What is the **fundamental frequency** here if T=20ms, 16.67ms, 2.5ms?:



$$f = \frac{1}{T}$$

What **RANGE** of frequencies are here?

System response varies with frequency

- Power system capacitors are specified in kVAR, which assumes a specific voltage and frequency.
- What happens to a capacitor's kVAR rating if we apply it at a lower voltage?
- What if we apply the capacitor at a higher frequency?
- What happens to line reactance as frequency increases?

$$X_C = \frac{1}{\omega C}$$

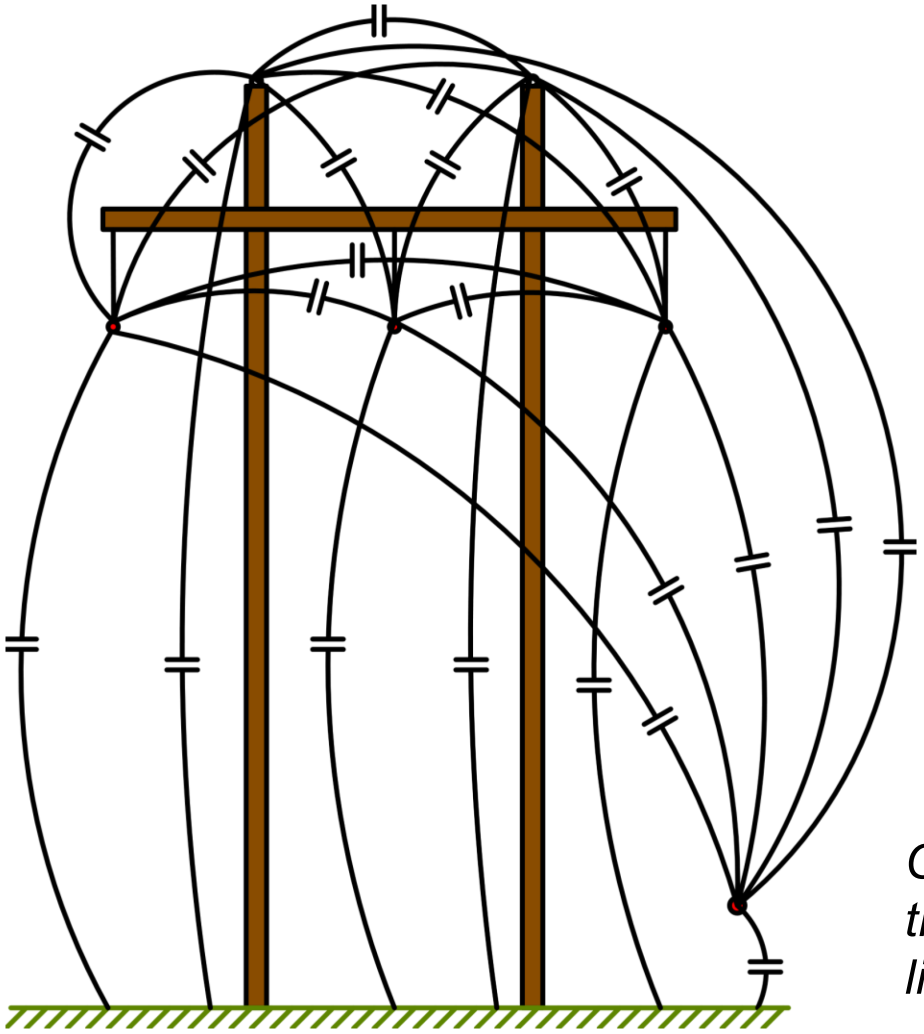
$$Z_C = -jX_C$$

$$X_L = \omega L$$

$$Z_L = jX_L$$

$$\omega = 2\pi f$$

“Accidental Apparatus”



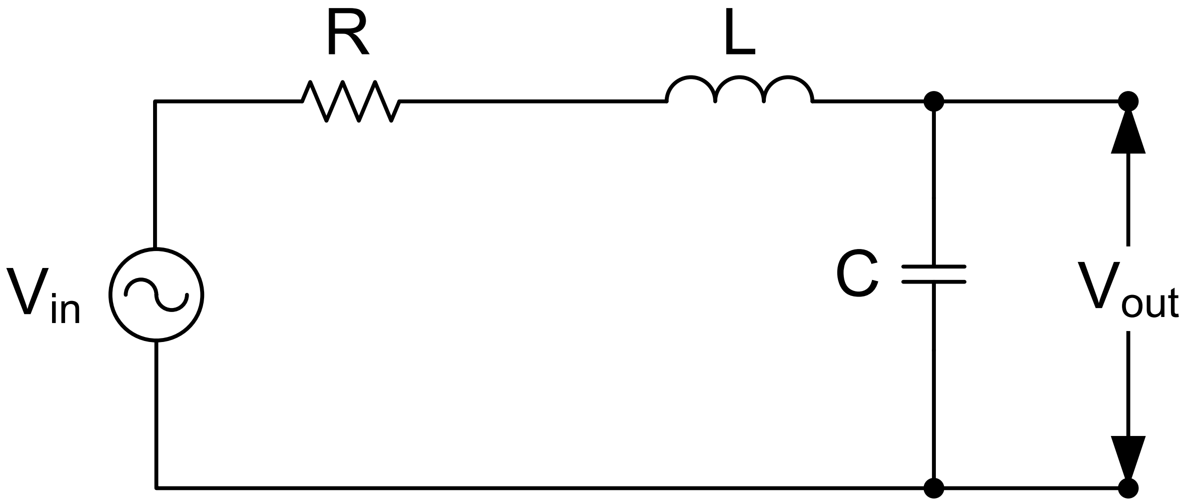
- Any two conductors are also a *__capacitor__*, even if one is the earth
- Conductors have resistance AND inductance
- There is *mutual __inductance__* between conductors
- These effects are frequency-dependent

Capacitive coupling for a three-phase transmission line and a fence wire.

“Accidental Apparatus”

- We build capacitively and inductively coupled circuits everywhere, whether we want to or not.
- Electric and magnetic fields may be the *path* in the power quality problem equation.

Does this look familiar?



- *Energy policy act of 2005 directed the designation of “energy corridors” for electric transmission lines and gas and oil pipelines*
- *Effect of EPAct 2005 sec. 368 has been to create single shared corridors on federal lands*

Power system behavior is frequency-dependent

Finding the frequencies – The Fourier Series

- Any periodic function can be represented by an infinite sum of <u>harmonic</u>ally related sine and cosine functions. (FPQ, page 195+/-)

$$f(t) = a_v + \sum_{k=1}^{\infty} \left(a_k \cdot \cos\left(k \cdot \omega_0 \cdot t\right) + b_k \cdot \sin\left(k \cdot \omega_0 \cdot t\right)\right)$$

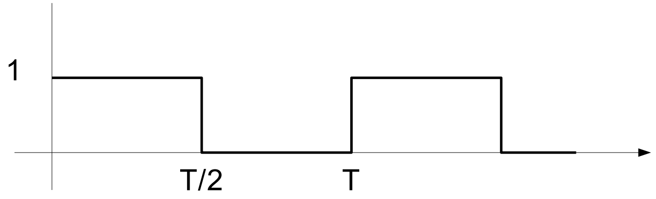
$$\omega_0 = 2\ \pi f$$

$$f = \frac{1}{T}$$

Fourier Coefficients

Harmonic: a multiple of the fundamental frequency

An example function, f(t):



The Fourier coefficients

- dc coefficient

$$a_V = \frac{1}{T} \cdot \int_{t_0}^{t_0+T} f(t)\, dt$$

- The k*th* value of a_k

$$a_k = \frac{2}{T} \cdot \int_{t_0}^{t_0+T} f(t) \cdot \cos\left(k \cdot \omega_0 \cdot t\right) dt$$

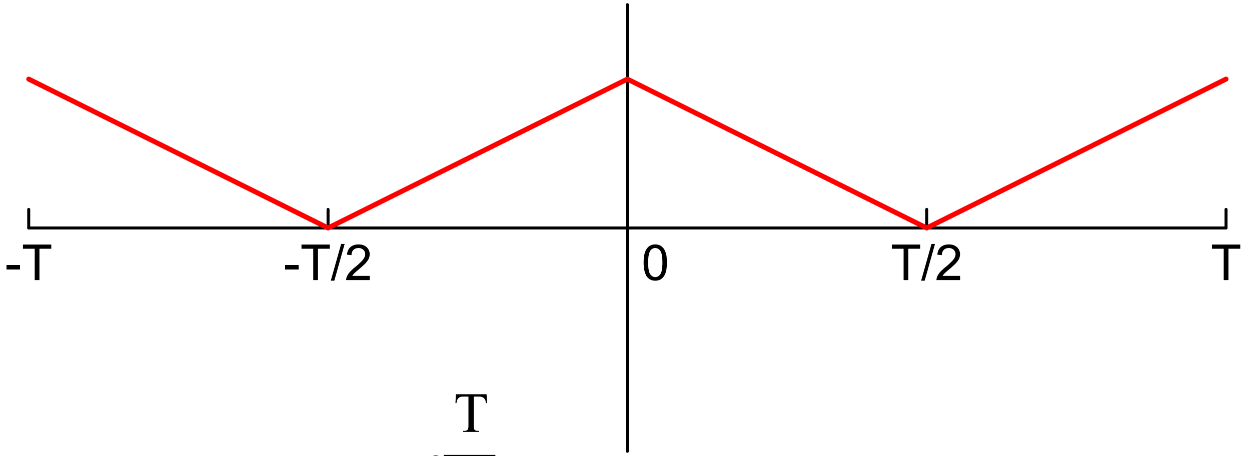
- The k*th* value of b_k

$$b_k = \frac{2}{T} \cdot \int_{t_0}^{t_0+T} f(t) \cdot \sin\left(k \cdot \omega_0\right) dt$$

Symmetry simplifies the Fourier Series

- Even function symmetry:

Test: $f(t) = f(-t)$



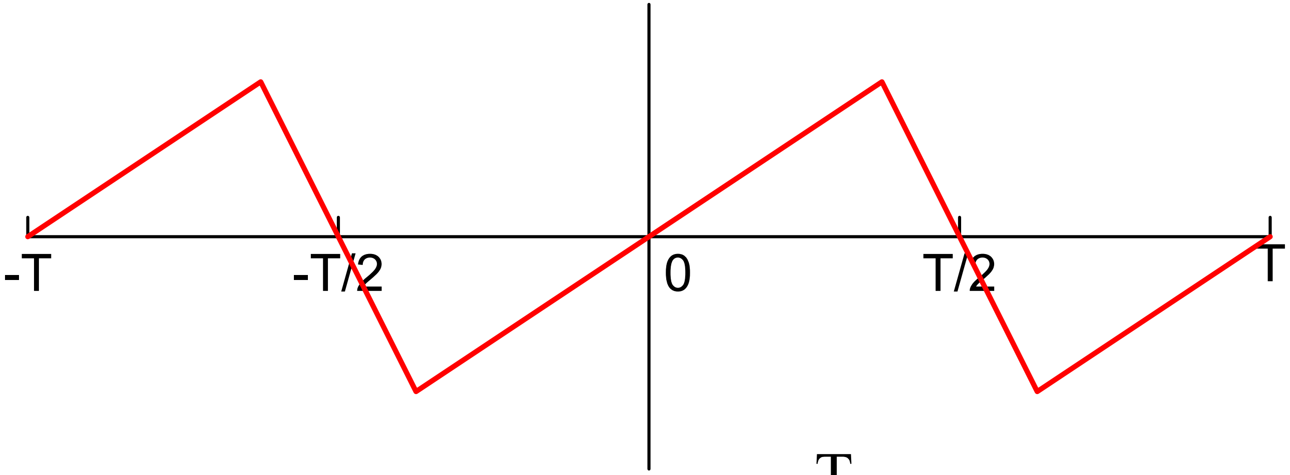
If you don't have symmetry, see if moving t_0 will make the function symmetrical.

$$a_v = \frac{2}{T} \cdot \int_0^{\frac{T}{2}} f(t)\, dt \qquad a_k = \frac{4}{T} \cdot \int_0^{\frac{T}{2}} f(t) \cdot \cos\left(k \cdot \omega_0 \cdot t\right) dt \qquad b_k = 0 \text{ for all k}$$

Symmetry simplifies the Fourier Series

- Odd function symmetry:

Test: $f(t) = -f(-t)$

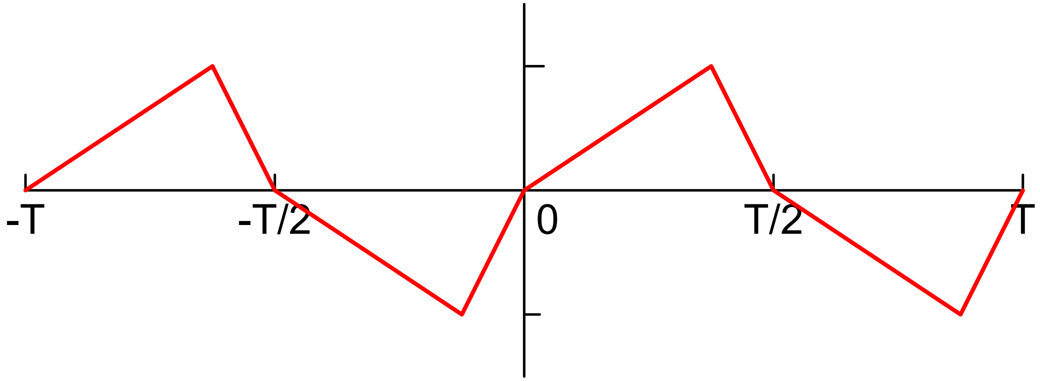


$a_v = 0 \quad a_k = 0$ for all k $\quad b_k = \frac{4}{T} \cdot \int_0^{\frac{T}{2}} f(t) \cdot \sin\left(k \cdot \omega_0 \cdot t\right) dt$

Symmetry simplifies the Fourier Series

- Half-Wave Symmetry:

Test: $f(t) = -f\left(t - \frac{T}{2}\right)$



$a_v = 0$ for all k

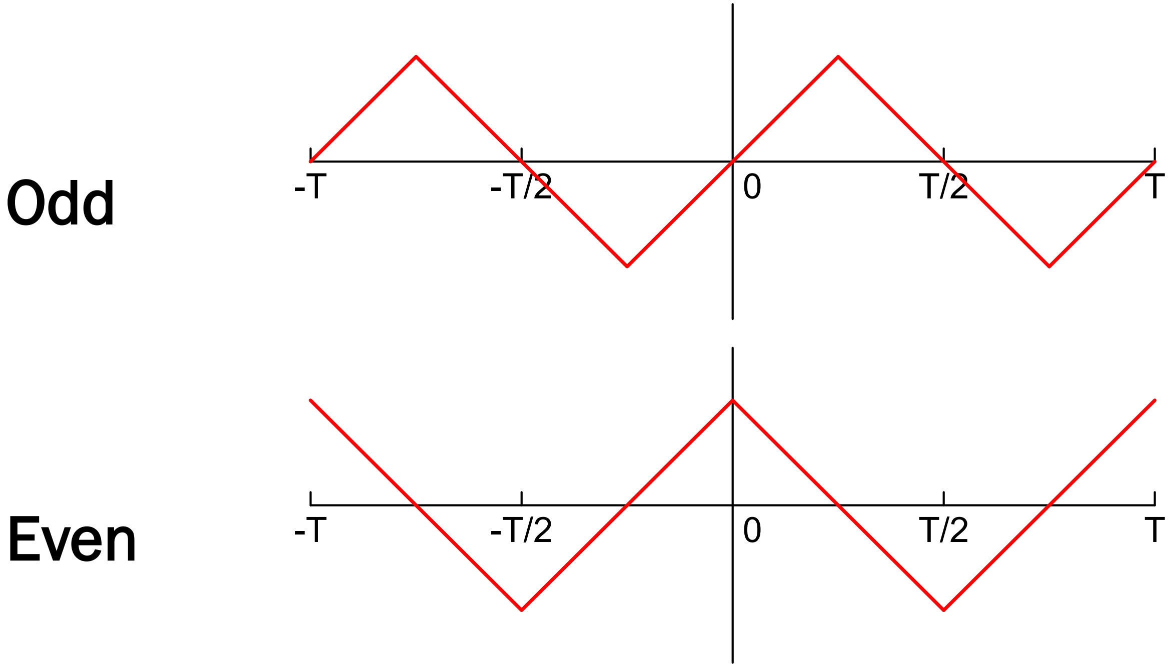
$a_k = 0$ $b_k = 0$ for k even

$$a_k = \frac{4}{T} \cdot \int_0^{\frac{T}{2}} f(t) \cdot \cos(k \cdot \omega_0 \cdot t)\, dt \qquad b_k = \frac{4}{T} \cdot \int_0^{\frac{T}{2}} f(t) \cdot \sin(k \cdot \omega_0 \cdot t)\, dt$$

for k odd

Symmetry simplifies the Fourier Series

- Quarter-wave symmetry:
  - Waveform has half-wave symmetry AND symmetry about the midpoints of the positive and negative half cycles
  - Can always be made even or odd



Symmetry simplifies the Fourier Series

Odd, Quarter-wave symmetry

$a_v = 0$

$a_k = 0$ for all k

$b_k = 0$ for k even

$$b_k = \frac{8}{T} \cdot \int_0^{\frac{T}{4}} f(t)\sin(k \cdot \omega_0 \cdot t)\,dt$$

Even, Quarter-wave symmetry

$a_v = 0$

$a_k = 0$ for k even

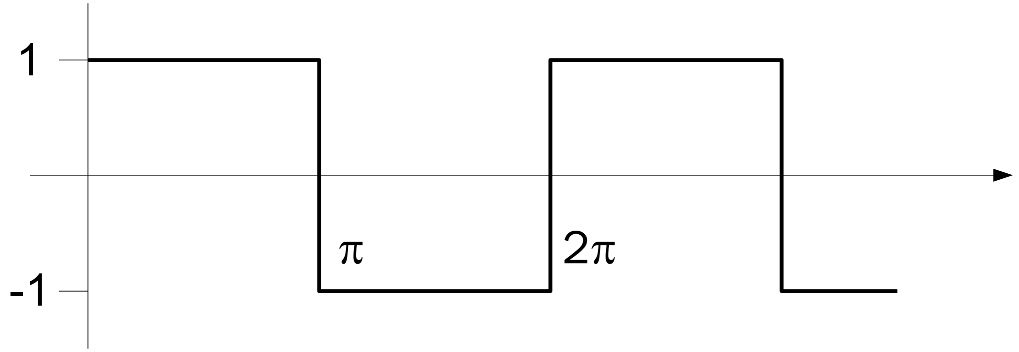
$b_k = 0$ for all k

$$a_k = \frac{8}{T} \cdot \int_0^{\frac{T}{4}} f(t)\cos(k \cdot \omega_0 \cdot t)\,dt$$

for k odd

Fourier Series Example

- We'll find the Fourier Series of a square wave:



- This function has odd, half, and quarter-wave symmetry.

If you don't have some simplifying symmetry, try moving the location of t=0.

Fourier Series of a square wave

- The only remaining coefficients are:

$$b_k = \frac{8}{T} \cdot \int_0^{\frac{T}{4}} \sin(k \cdot \omega_o \cdot t)\, dt \qquad \text{For odd k}$$

- Solving this integral for odd k yields:

$$b_k = \frac{4}{k \cdot \pi}$$

From Prime:

$$k := 1, 3 .. 5$$

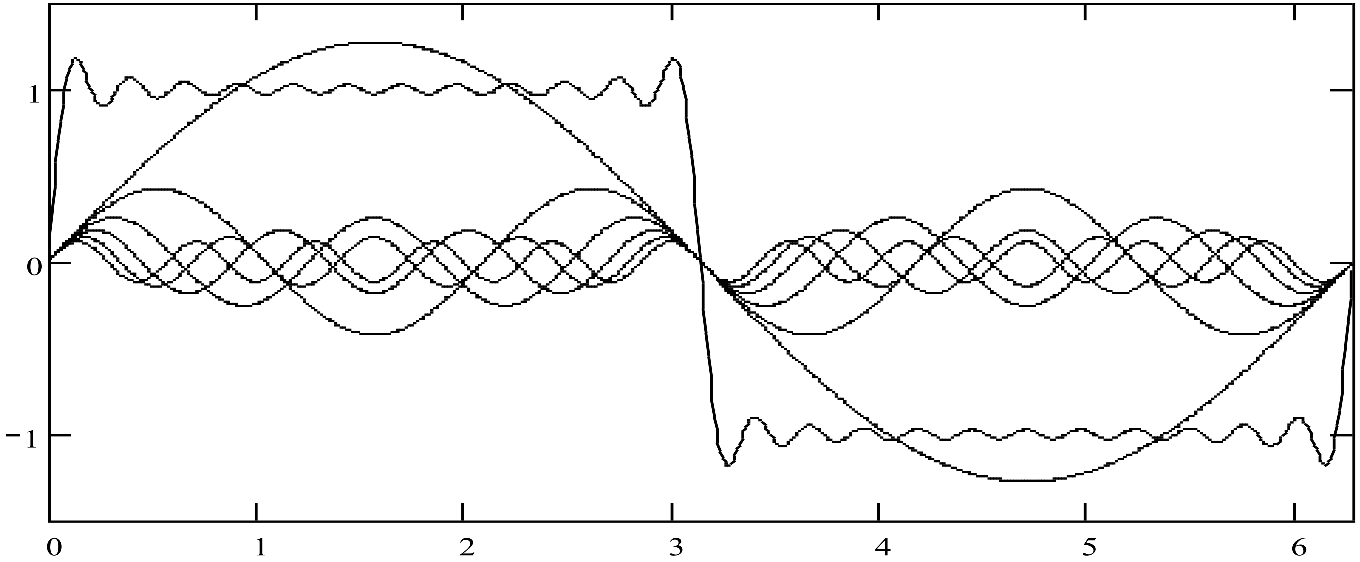
$$b_k = \frac{8}{T} \cdot \int_0^{\frac{T}{4}} \sin\left(k \cdot \frac{2\,\pi}{T} \cdot t\right) dt \rightarrow \begin{bmatrix} b_1 = \frac{4}{\pi} \\ b_3 = \frac{4}{3 \cdot \pi} \\ b_5 = \frac{4}{5 \cdot \pi} \end{bmatrix}$$

$$\omega_0 = 2\,\pi f \qquad f = \frac{1}{T}$$

The answer…

- The Fourier Series of the square wave is given by:

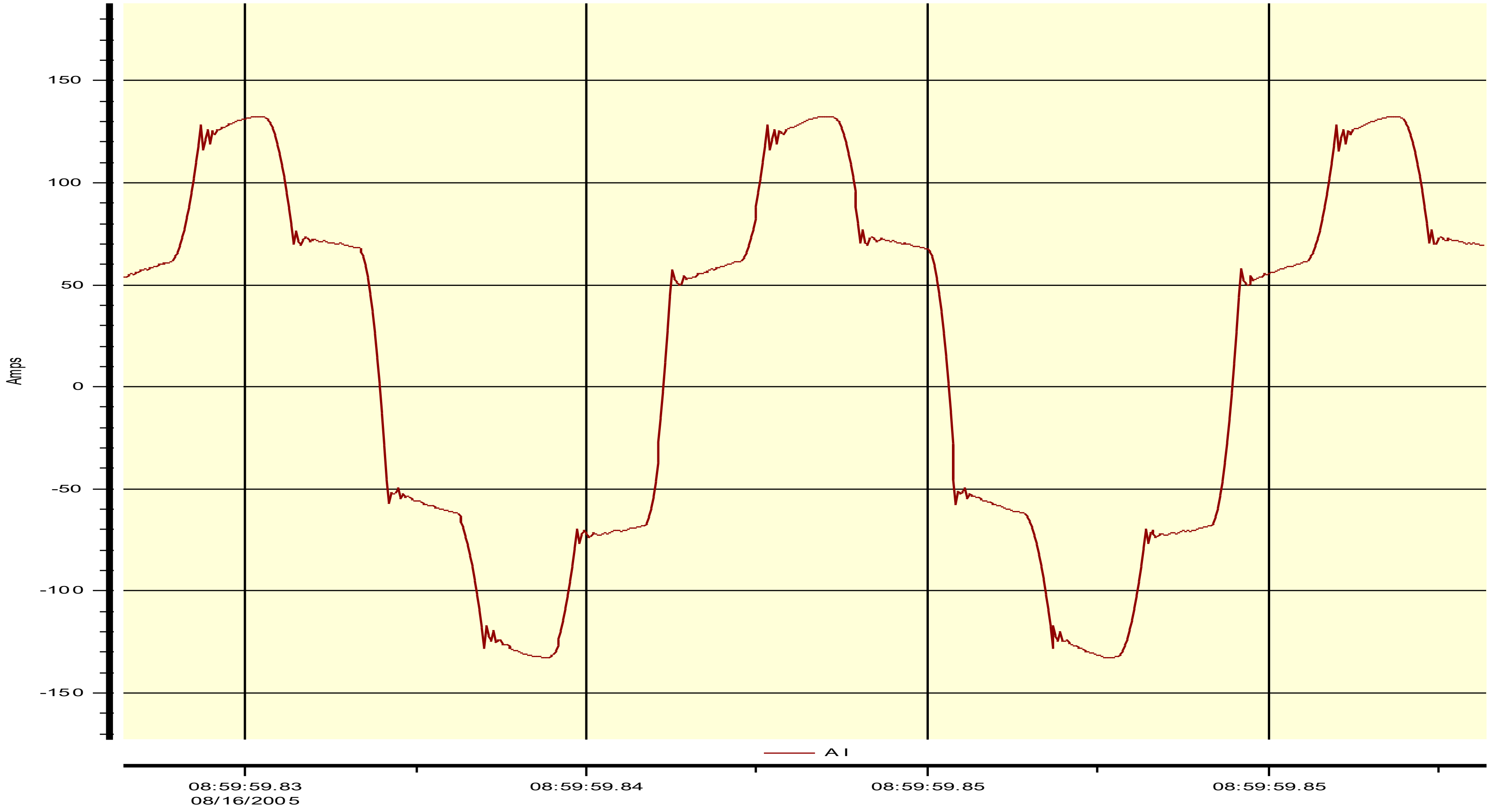
$$V = \frac{4}{\pi} \cdot \left[\sum_{k=1}^{\infty} \left(\frac{1}{k} \cdot \sin\left(k \cdot \omega_o \cdot t\right) \right) \right] \quad \text{For odd k}$$



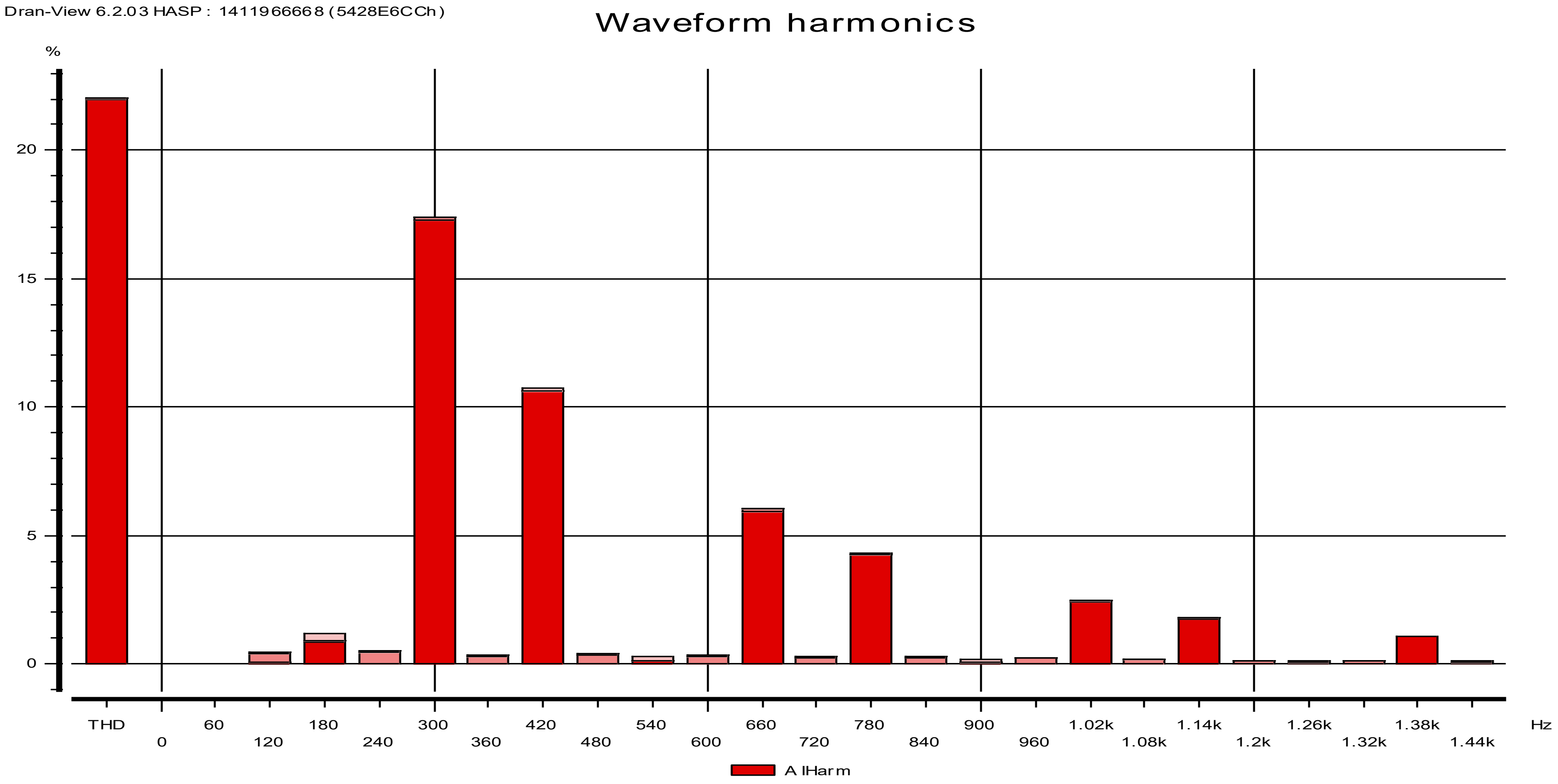
Computer Analysis

- In the real world, we have sampled data of a complex waveform.
- DFT – Discrete Fourier Transform
  - Used to determine the harmonic spectrum of a periodic signal made up of discrete points.
- FFT – Fast Fourier Transform
  - Optimized implementation of the DFT for computer analysis. This is the method used by most software.

Computer Analysis – a current waveform

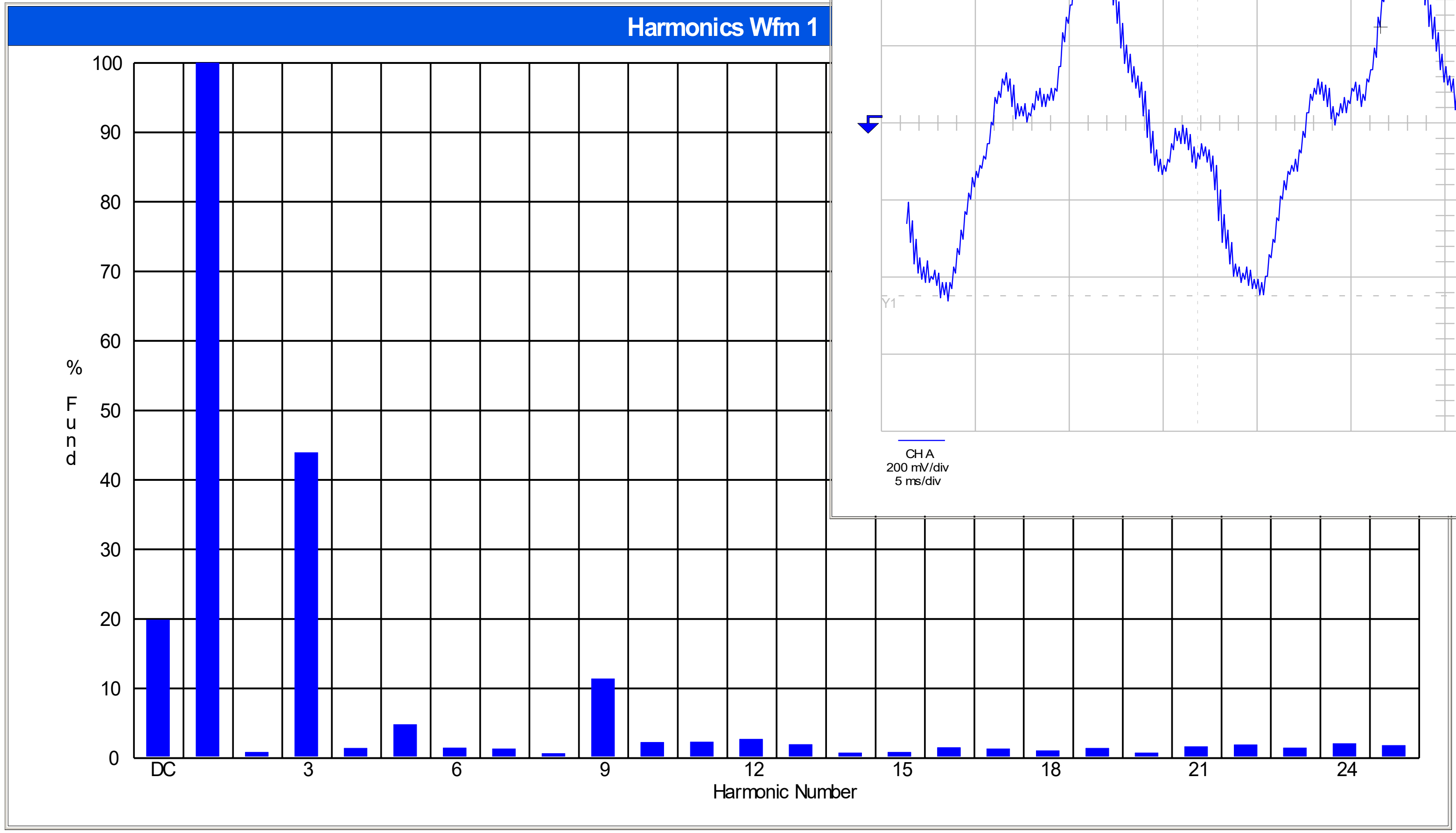


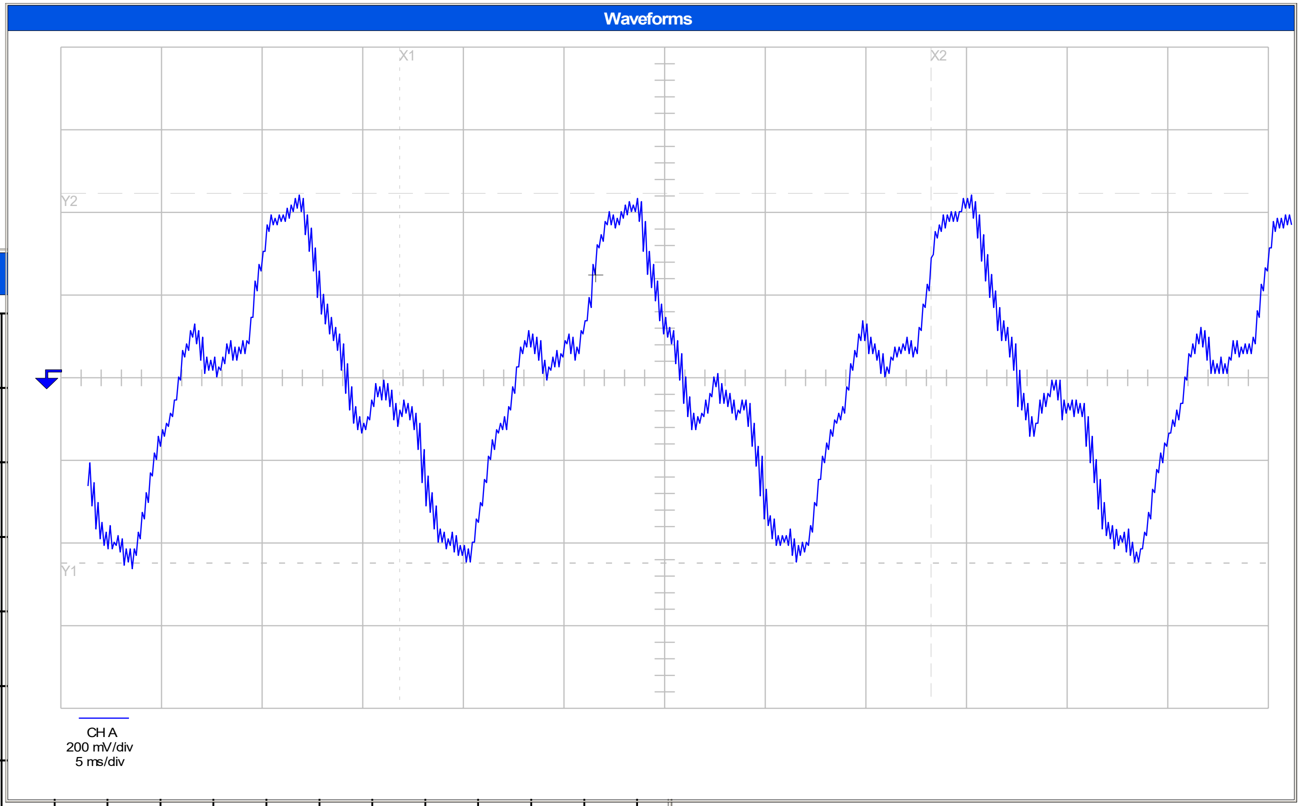
The waveform's harmonic spectrum



Note – magnitudes are in percent of the fundamental, so the fundamental is omitted.

Another waveform and its spectrum





Next time…

- Power electronics review

You should have enough in the lecture notes to complete Homework 1.