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College of Engineering

# ECE 528 – Understanding Power Quality

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

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Lecture 3



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## Today…

- The multi-frequency power system
- Frequency's impact on the power system
- Accidental apparatus
- Finding the frequencies
- "Signature" waveforms

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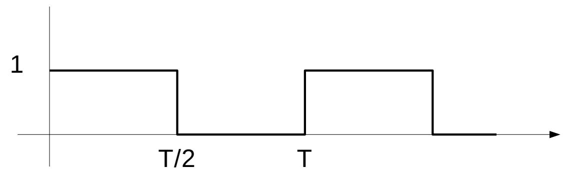
## The Multi-frequency power system

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



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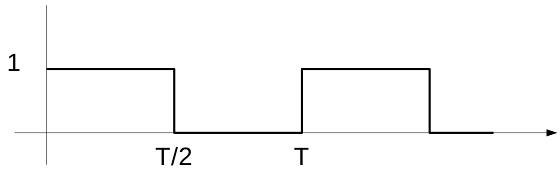
## The Multi-frequency power system

- 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?

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

$$X_L = j\omega L$$

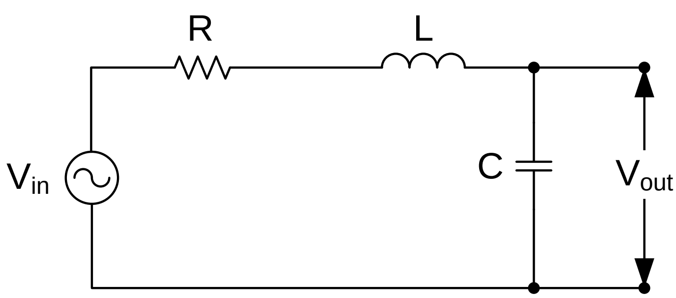
$$\omega = 2\pi f$$





# Accidental Apparatus

Does this look familiar?



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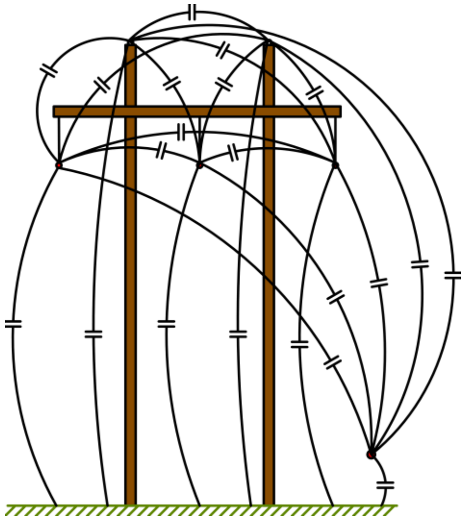
## "Accidental Apparatus"

- There is *mutual inductance* between conductors
- Any two conductors are also a *capacitor*
- Effects are frequency-dependent

*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*





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## Finding the frequencies – The Fourier Series

- Any periodic function can be represented by an infinite sum of harmonically related sine and cosine functions.

(FPQ, page 185+/-)

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

Fourier Coefficients

## The Fourier coefficients

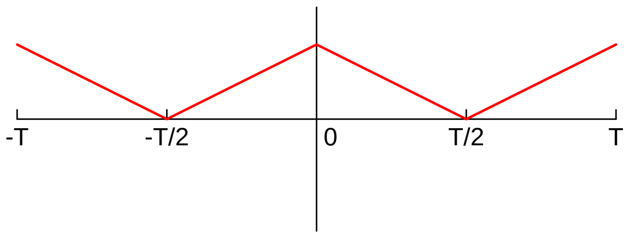
- dc coefficient $$a_V = \frac{1}{T} \cdot \int_{t_0}^{t_0+T} f(t)\, dt$$
- The k*th* value of $a_k$ $$a_k = \frac{2}{T} \cdot \int_{t_0}^{t_0+T} f(t) \cdot \cos(k \cdot \omega_0 \cdot t)\, dt$$
- The k*th* value of $b_k$ $$b_k = \frac{2}{T} \cdot \int_{t_0}^{t_0+T} f(t) \cdot \sin(k \cdot \omega_0)\, dt$$





## Symmetry simplifies the Fourier Series

- Even function symmetry: $f(t) = f(-t)$




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

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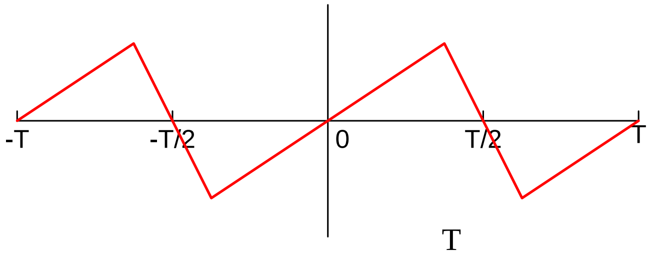
# Symmetry simplifies the Fourier Series

- Odd function symmetry: $f(t) = -f(-t)$




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



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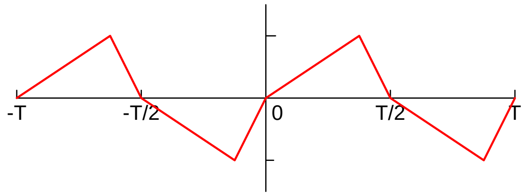
# Symmetry simplifies the Fourier Series

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




$a_v = 0$ for all k

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

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

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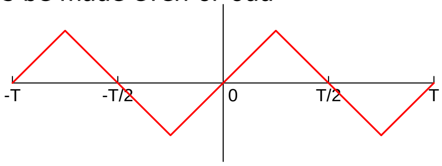
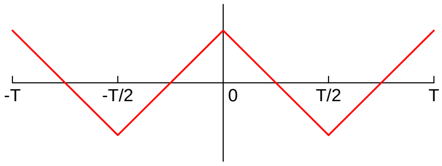
# Symmetry simplifies the Fourier Series

- 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

**Odd**




**Even**



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# 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

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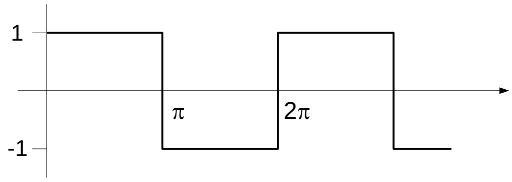
## Fourier Series Example

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




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



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## Fourier Series of a square wave

- The only remaining coefficients are:

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

- Solving this integral for odd k yields:

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

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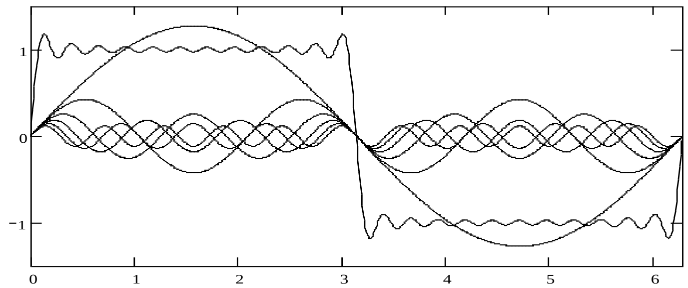
# The answer…

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

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



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# 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.

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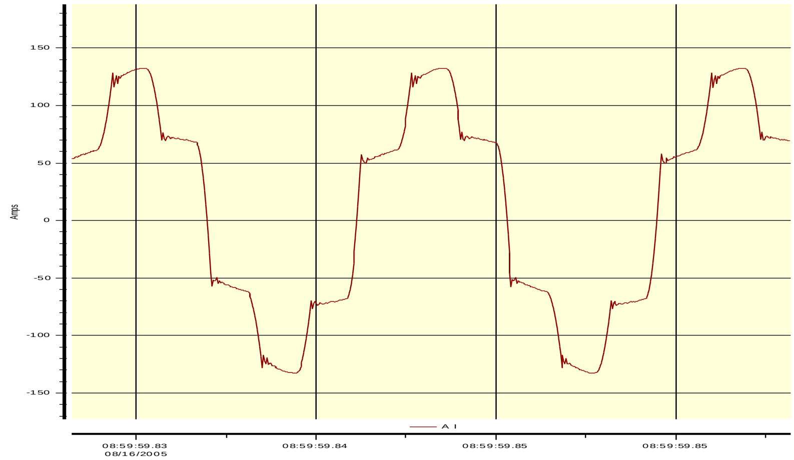
# Computer Analysis – a current waveform



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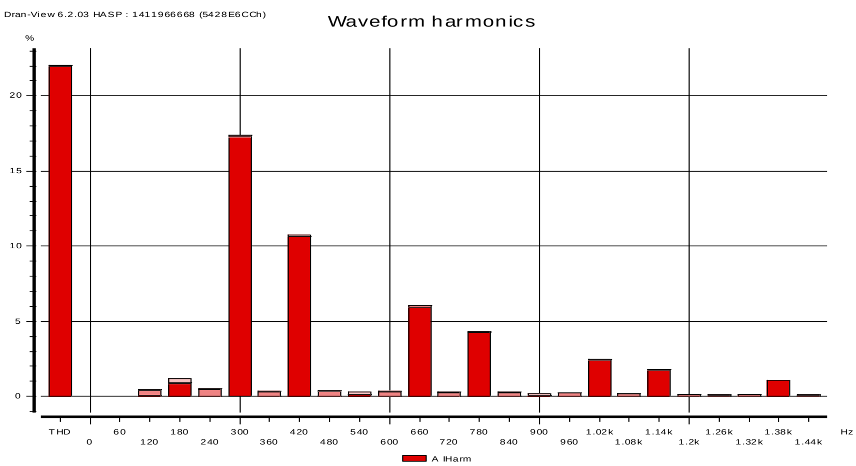
# The waveform's harmonic spectrum



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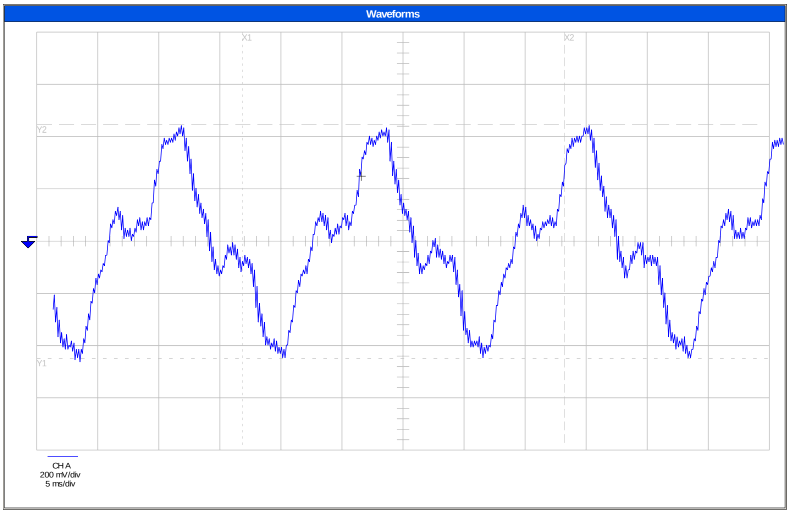
# Another waveform…



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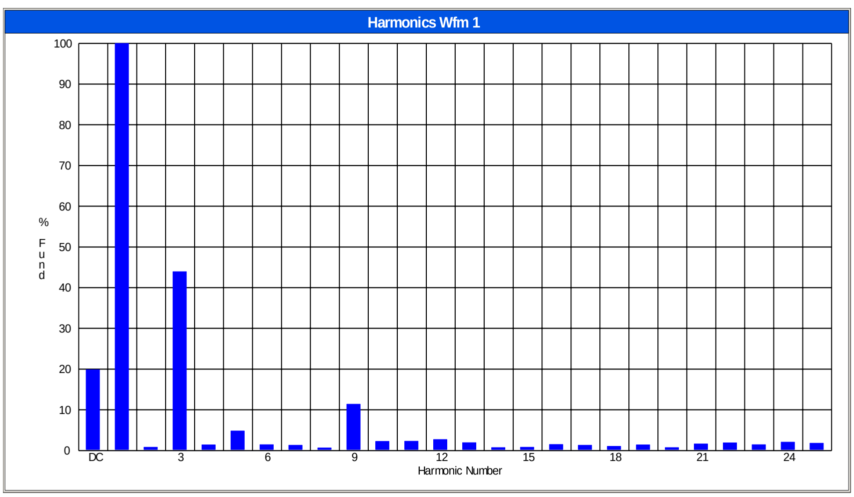
# And its harmonic spectrum



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## Next time…

- Power electronics review

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