ELG4126: Harmonics

Electrical Pollution

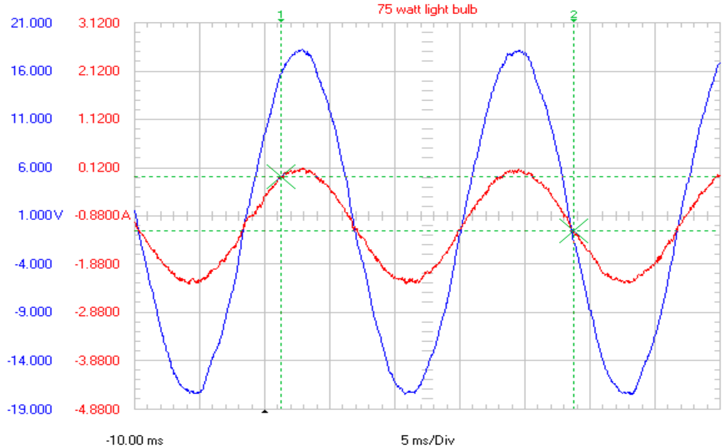
Anything that Deviates from a Normal Sinusoid!

Harmonics: Where it Comes from?

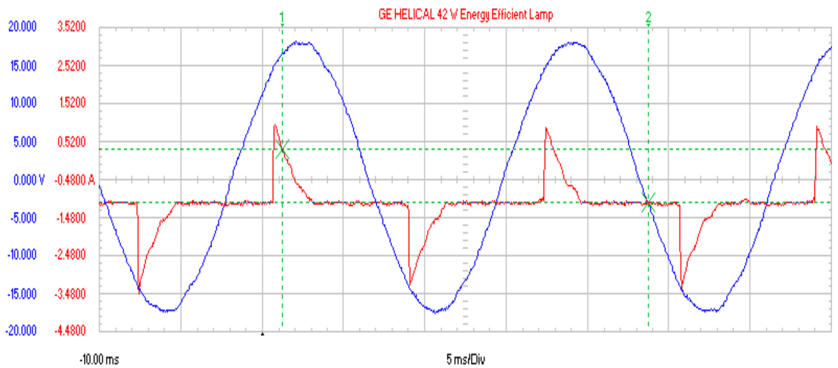
1972 : Oil embargo forced the world to become more energy efficient.

Originally, equipment was designed to operate using **short pulses** of current instead of **continuous current.**

Variable speed frequency drives, CFD lighting, dimmer switches, computers, TV's, and most other modern electronic devices are energy efficient but are nonlinear loads.



Waveforms of a 75 watt incandesent light bulb



The waveforms show the voltage in blue and the pulses of from an energy efficient GE HELICAL 42 W lamp

More than one Wave!

Harmonic is a frequency that is an integer (whole number) multiple (2nd, 3rd, 4th, 5th, etc.) of the fundamental frequency. The fundamental frequency on power distribution lines is 60 Hz.

When more than one sine wave are combined, they form a **complex wave**.

At any given time, each wave will have some amplitude value.

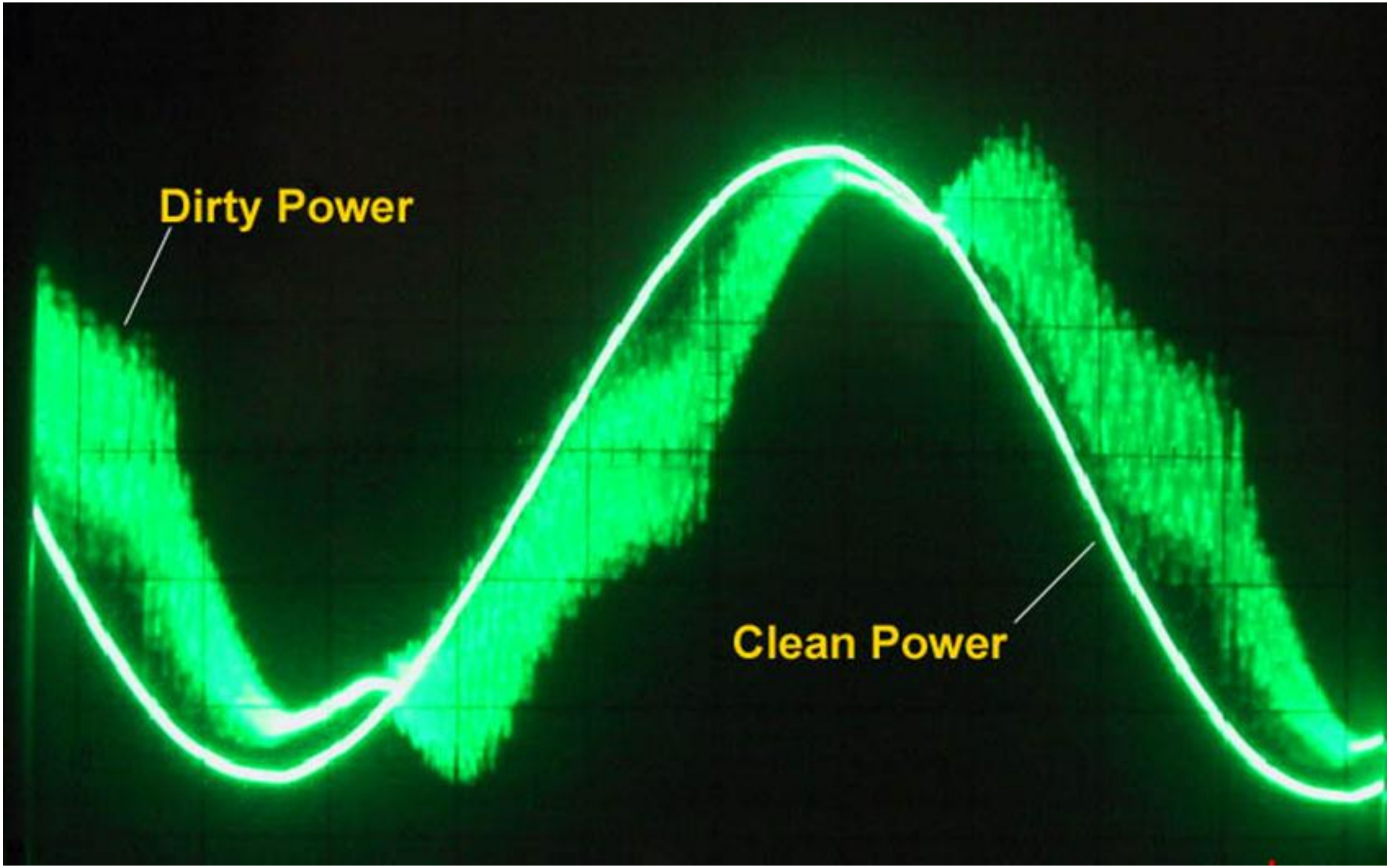
$E_1(t_1)$:= Amplitude value of sine wave 1 at time 1

$E_2(t_1)$:= Amplitude value of sine wave 2 at time 1

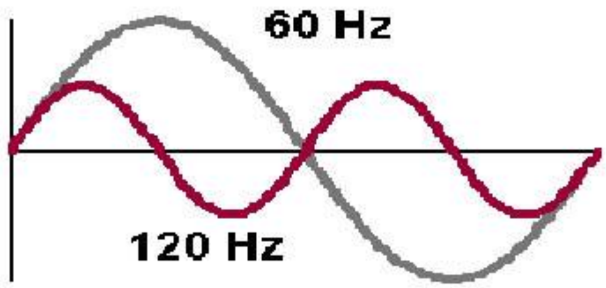
The amplitude value of the total complex wave is the sum of the values of the waves.

$$E_T(t_1) = E_1(t_1) + E_2(t_1)$$

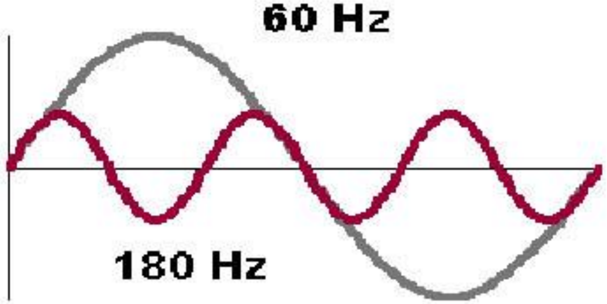
Power: Clean and Dirty



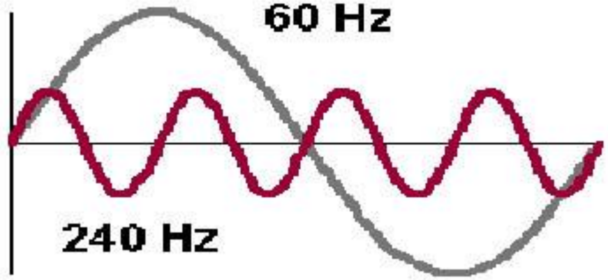
Second Harmonics



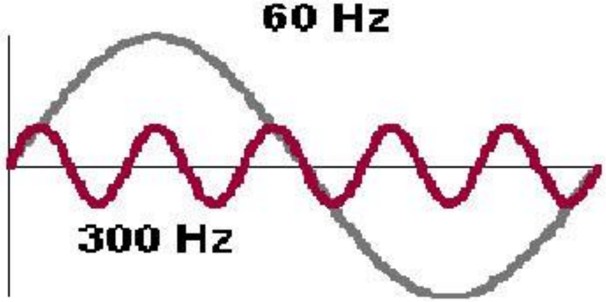
Third Harmonics



Fourth Harmonics

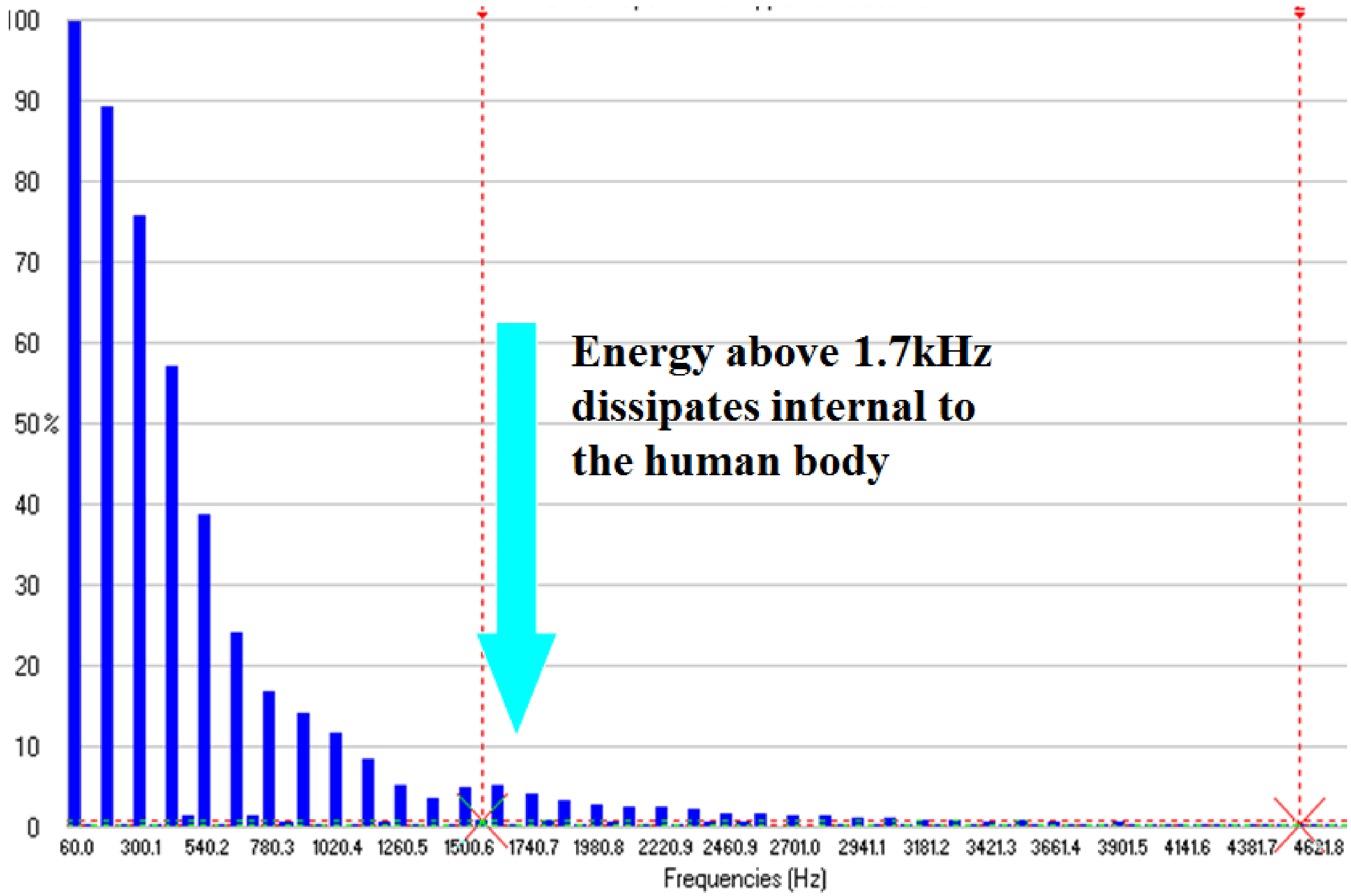


Fifth Harmonics

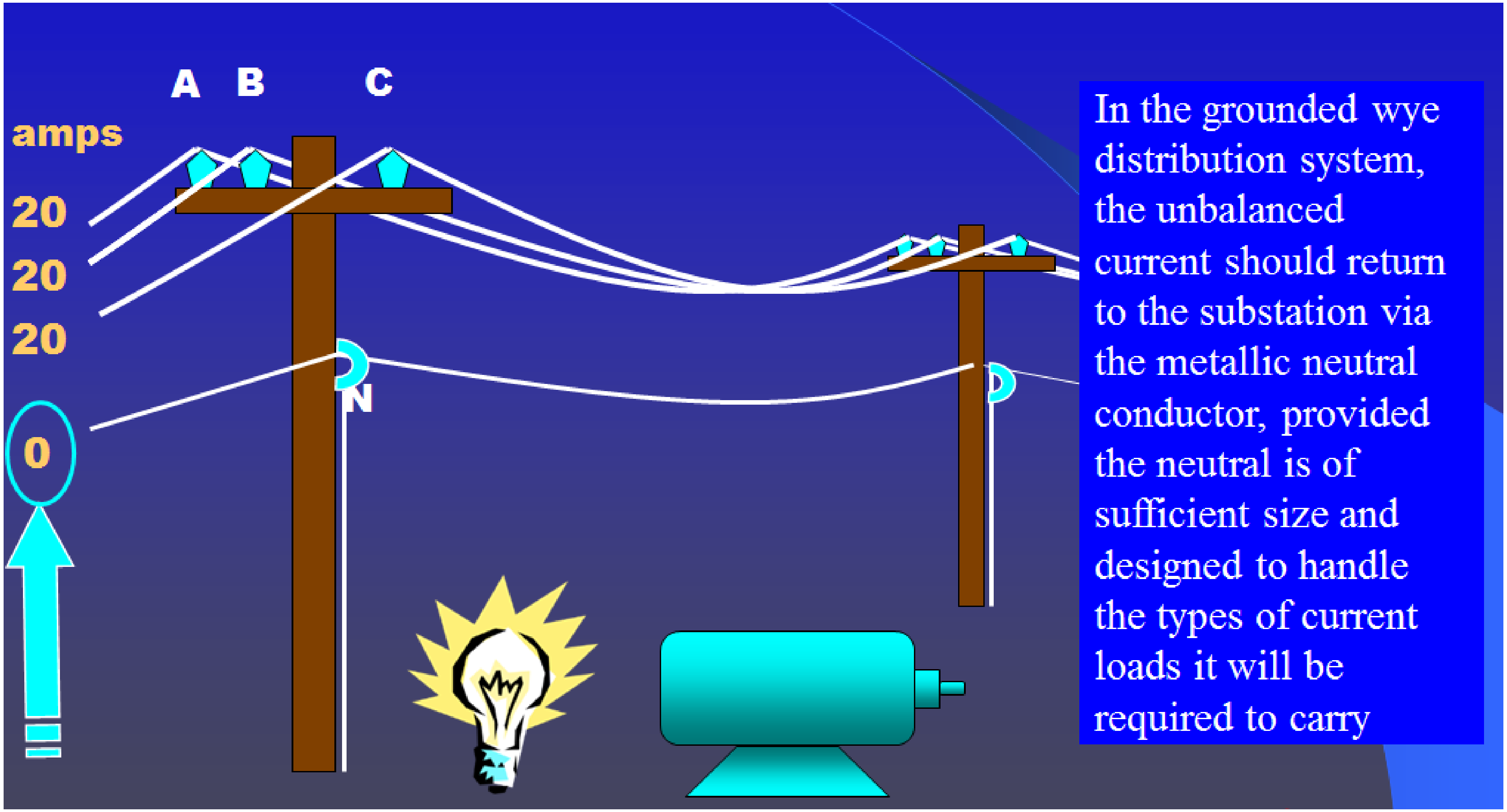


Harmonics!

Cause electric meters to read inaccurately; Cause motors and transformers to burn out; Cause neutral wires in a system to overheat; Cause electronic equipment to fail; Affect human health?

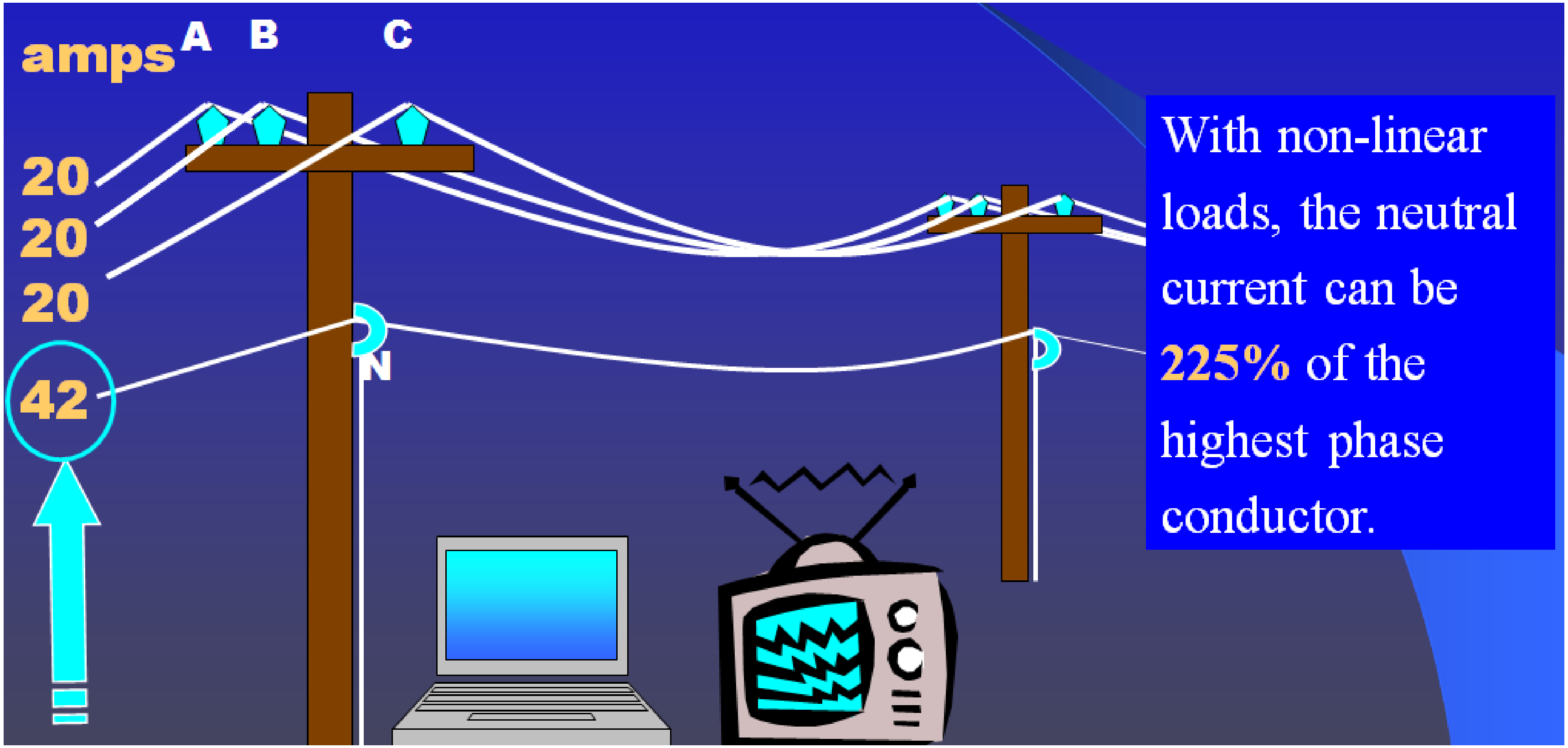


In Theory: Balanced Y-Circuit



Source: Dave Stetzer

Unbalanced Y Circuit



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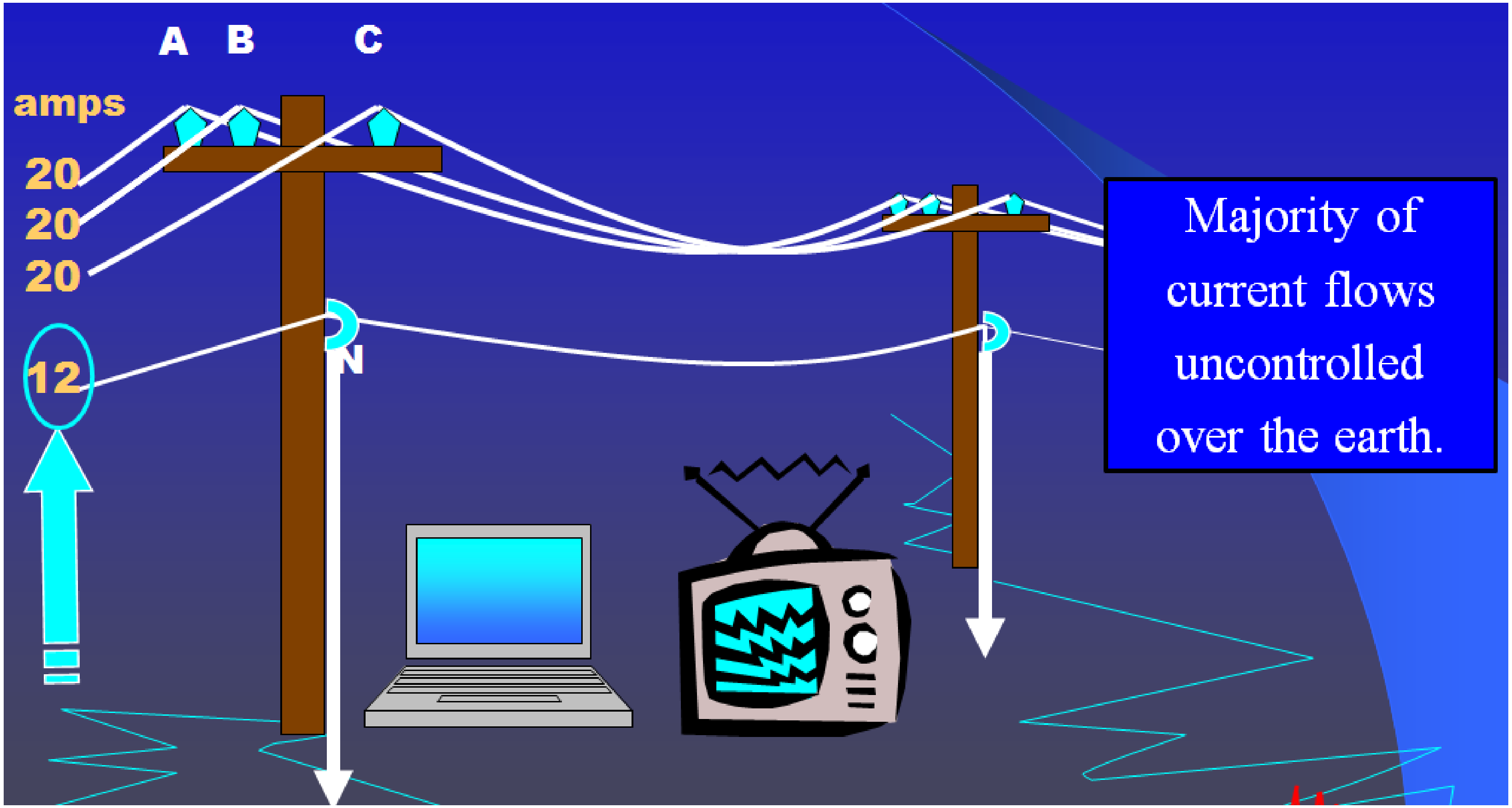
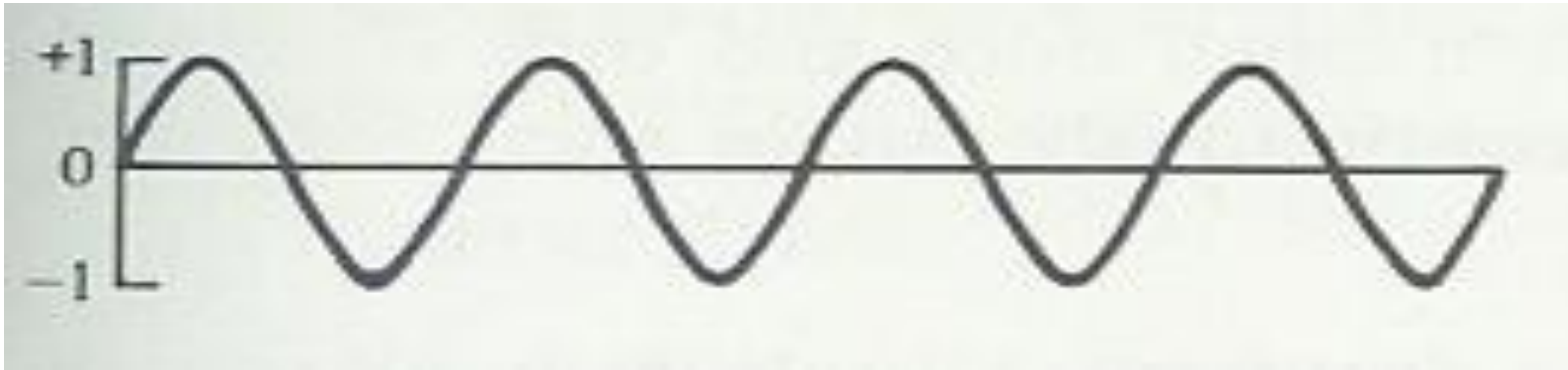


Source: Dave Stetzer

Example



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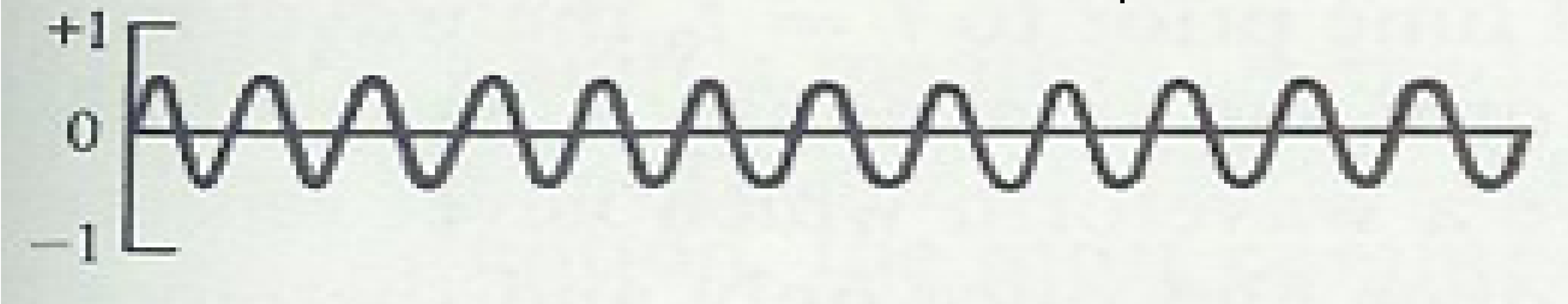

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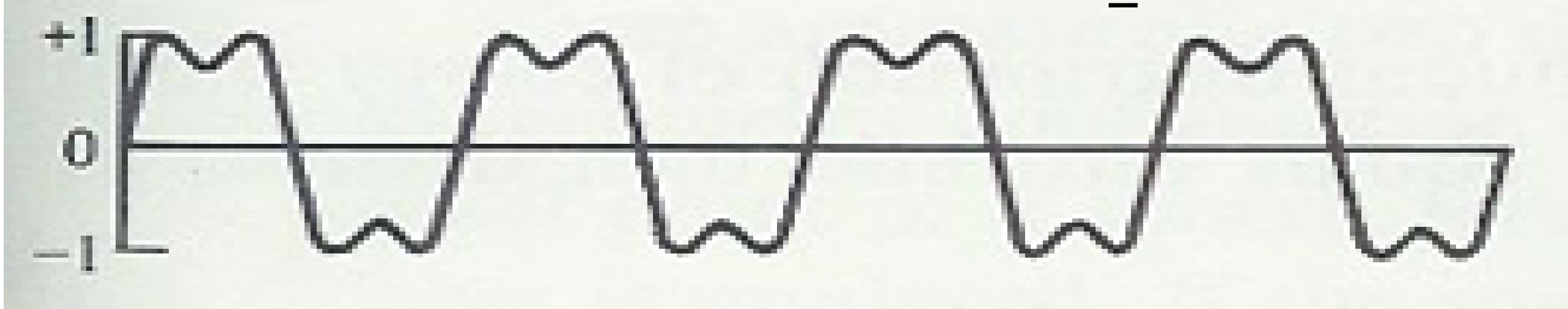


Greatest Common Denominator

Combining sine waves results in a **complex periodic wave**.

This complex wave has a frequency which is the **greatest common denominator** of the frequencies of the component waves.

Greatest common denominator = biggest number by which you can divide both frequencies and still come up with a whole number (integer).

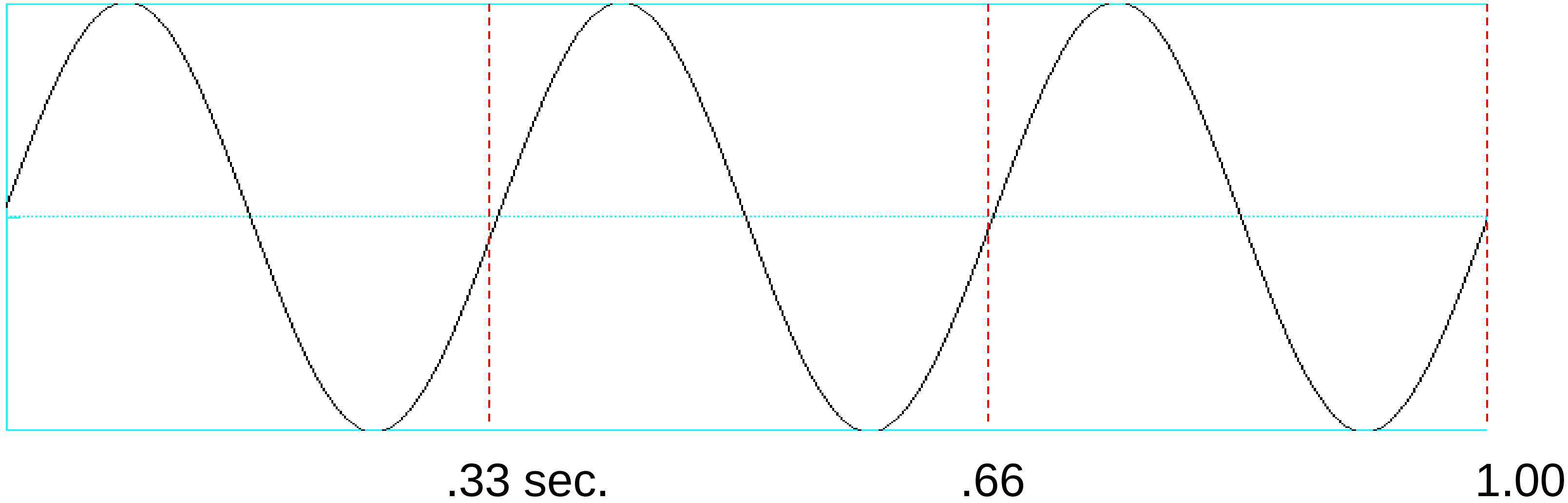
Example

Wave 1: 300 Hz

Wave 2: 500 Hz

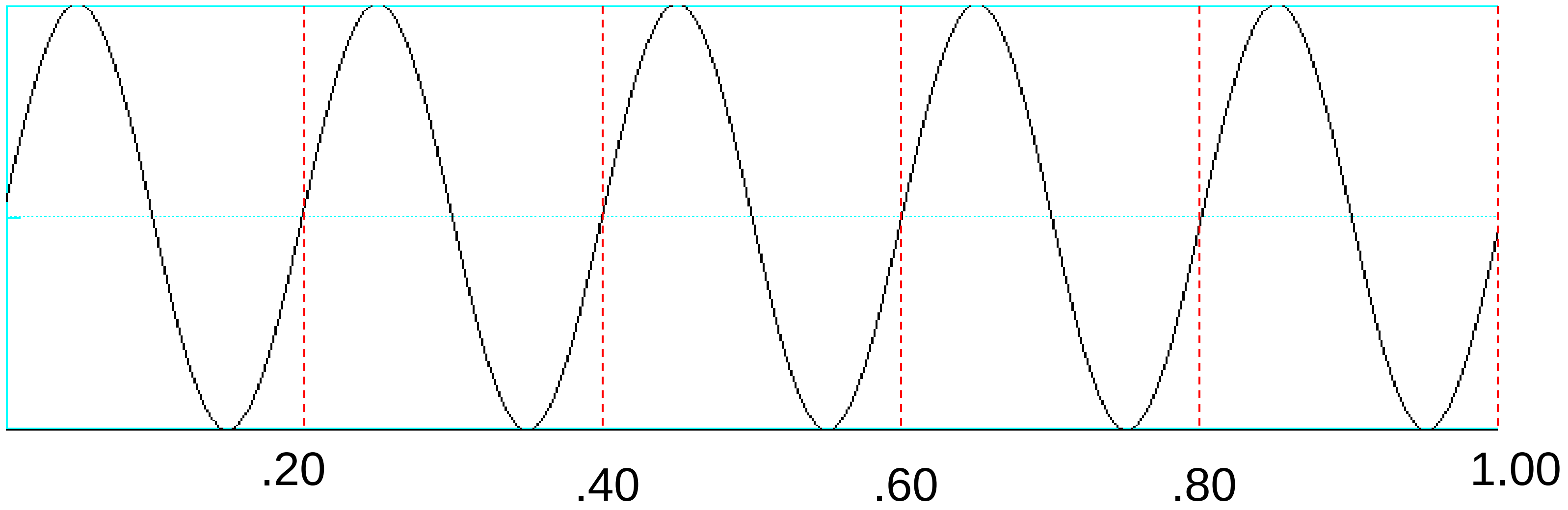
Fundamental Frequency: 100 Hz

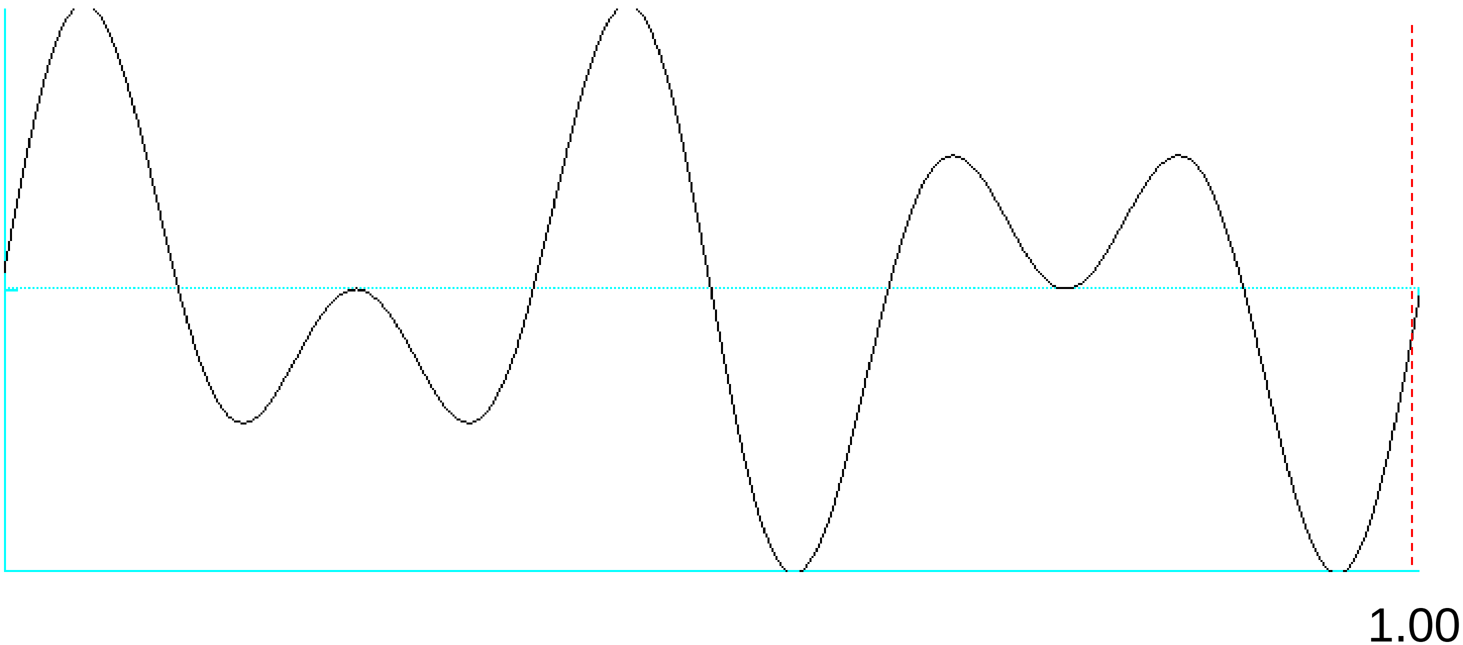
3 Hz



What is the common denominator for this combination

5 Hz





Combination of 3 and 5 Hz waves

(period = 1 second)

(frequency = 1 Hz)

Fourier's Theorem

Joseph Fourier (1768-1830)

- French mathematician
- Studied heat and periodic motion

The idea:

any complex periodic wave can be constructed out of a combination of different sinewaves.

The sinusoidal (sine wave) components of a complex periodic wave = **harmonics**

Harmonics

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos\frac{2\pi n t}{T} + \sum_{n=1}^{\infty} b_n \sin\frac{2\pi n t}{T}$$

$$f(t) = \underbrace{\frac{a_0}{2}}_{\text{DC Part}} + \underbrace{\sum_{n=1}^{\infty} a_n \cos(n\omega_0 t)}_{\text{Even Part}} + \underbrace{\sum_{n=1}^{\infty} b_n \sin(n\omega_0 t)}_{\text{Odd Part}}$$

DC Part Even Part Odd Part

T is a period of all the above signals

Harmonics

Define $\omega_0 = 2\pi f_0 = \frac{2\pi}{T}$, called the *fundamental angular frequency*.

Define $\omega_n = n\omega_0$, called the *n*-th *harmonic* of the periodic function.

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos n\omega_0 t + \sum_{n=1}^{\infty} b_n \sin n\omega_0 t$$

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos \omega_n t + \sum_{n=1}^{\infty} b_n \sin \omega_n t$$

Harmonics

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos \omega_n t + \sum_{n=1}^{\infty} b_n \sin \omega_n t$$

$$= \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos \omega_n t + b_n \sin \omega_n t)$$

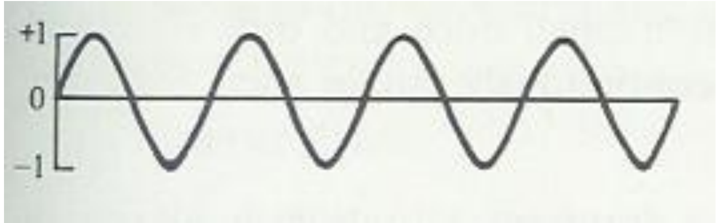
$$= \frac{a_0}{2} + \sum_{n=1}^{\infty} \sqrt{a_n^2 + b_n^2} \left(\frac{a_n}{\sqrt{a_n^2 + b_n^2}} \cos \omega_n t + \frac{b_n}{\sqrt{a_n^2 + b_n^2}} \sin \omega_n t \right)$$

$$= \frac{a_0}{2} + \sum_{n=1}^{\infty} \sqrt{a_n^2 + b_n^2} \left(\cos \theta_n \cos \omega_n t + \sin \theta_n \sin \omega_n t \right)$$

$$= C_0 + \sum_{n=1}^{\infty} C_n \cos(\omega_n t - \theta_n)$$

Waveform and Spectrum

Waveform



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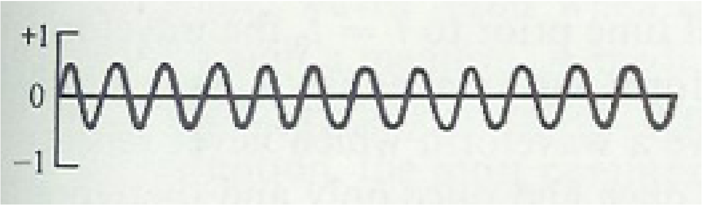

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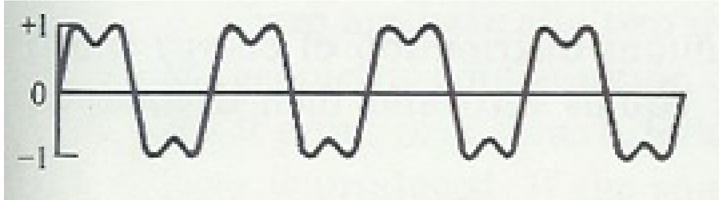
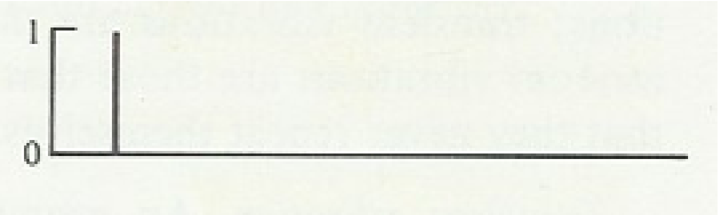


Power Spectrum



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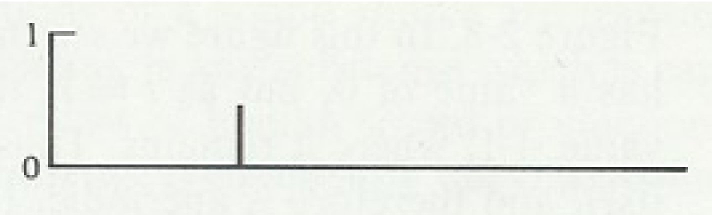

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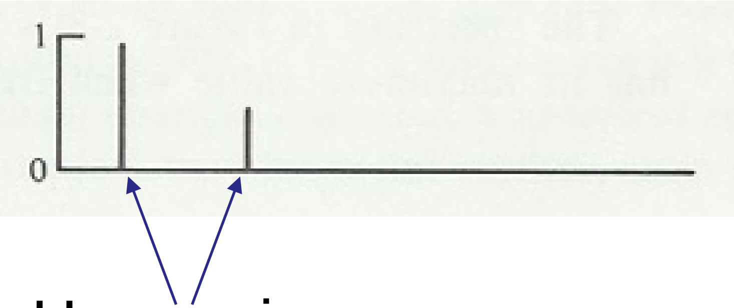


Harmonics

Fourier's Theorem

The component sinusoids (harmonics) of any complex periodic wave:

All have a frequency that is an integer multiple of the fundamental frequency of the complex wave.

This is equivalent to saying:

All component waves complete an integer number of periods within each period of the complex wave.

Consider a complex wave with a fundamental frequency of 100 Hz.

Harmonic 1 = 100 Hz

Harmonic 2 = 200 Hz

Harmonic 3 = 300 Hz

Harmonic 4 = 400 Hz

Harmonic 5 = 500 Hz

Why Harmonics Analysis ?

When a voltage and/or current waveform is distorted, it may cause abnormal operating conditions in a power system such as:

- Voltage Harmonics can cause additional heating in induction and synchronous motors and generators.
- Voltage Harmonics with high peak values can weaken insulation in cables, windings, and capacitors.
- Voltage Harmonics can cause malfunction of different electronic components and circuits that utilize the voltage waveform for synchronization or timing.
- Current Harmonics in motor windings can create electromagnetic interference (EMI).
- Current Harmonics flowing through cables can cause higher heating over and above the heating that is created from the fundamental component.
- Current Harmonics flowing through a transformer can cause higher heating over and above the heating that is created by the fundamental component.
- Current Harmonics flowing through circuit breakers and switch-gear can increase their heating losses.

Example

SINUSOIDAL VOLTAGE-NONSINIMUSOIDAL CURRENT

A periodic, sinusoidal voltage of instantaneous value $v = 200\sqrt{2}\sin\omega t$
Is applied to a nonlinear load impedance. The resulting instantaneous current is given by: $i = \sqrt{2}\left[20\sin\left(\omega t - 45^{o}\right) + 10\sin\left(2\omega t + 60^{o}\right) + 10\sin\left(3\omega t + 60^{o}\right)\right]$

Calculate the components **P, Q, D** of the apparent voltamperes and hence calculate the displacement factor, the distortion factor and the power factor.

Solution

$$v = 200\sqrt{2}\sin\omega t$$

$$i = \sqrt{2}\left[20\sin\left(\omega t - 45^{o}\right) + 10\sin\left(2\omega t + 60^{o}\right) + 10\sin\left(3\omega t + 60^{o}\right)\right]$$

The presence of the nonlinearity causes frequency components of current (i.e. the second and third harmonic terms) that are not present in the applied voltage.

The rms voltage and current at the supply are:

$$\tilde{V} = 200\,V$$

$$\tilde{I}^2 = 20^2 + 10^2 + 10^2$$

$$= 6 \times 10^2\,A^2$$

The apparent voltamperes at the input is therefore given by

$$S^2 = \tilde{V}^2\tilde{I}^2 = 200^2 \times 6 \times 10^2 = 24 \times 10^6 (VA)^2$$

In this example only the fundamental frequency components are common to both voltage and current. Therefore, the real power P and the apparent power Q are

$$P = \tilde{V}\tilde{I}_1 \cos\psi_1$$

ψ_1 = *displacement angle between the fundamental of the voltage and the fundamental of the current*

$$= 200 \times 20 \cos 45^o$$

$$= \frac{4000}{\sqrt{2}} W$$

$$Q = \tilde{V}\tilde{I}_1 \sin\psi_1$$

$$= 200 \times 20 \sin 45^o$$

$$= \frac{4000}{\sqrt{2}} VA$$

$$D^2 = \tilde{V}^2\left(\tilde{I}^2 - \tilde{I}_1^2\right)$$

$$= \tilde{V}^2\left(\tilde{I}_2 - \tilde{I}_3^2\right)$$

$$= 200^2\left(10^2 + 10^2\right) = 8\times 10^6 (VA)^2$$

$$P^2 + Q^2 + D^2 = \tilde{V}^2\tilde{I}^2$$

$$PF = \text{power factor} = \frac{P}{S} = \frac{\tilde{V}\tilde{I}_1 \cos\psi_1}{\tilde{V}\tilde{I}} = \left(\frac{\tilde{I}_1}{I}\right)(\cos\psi_1)$$

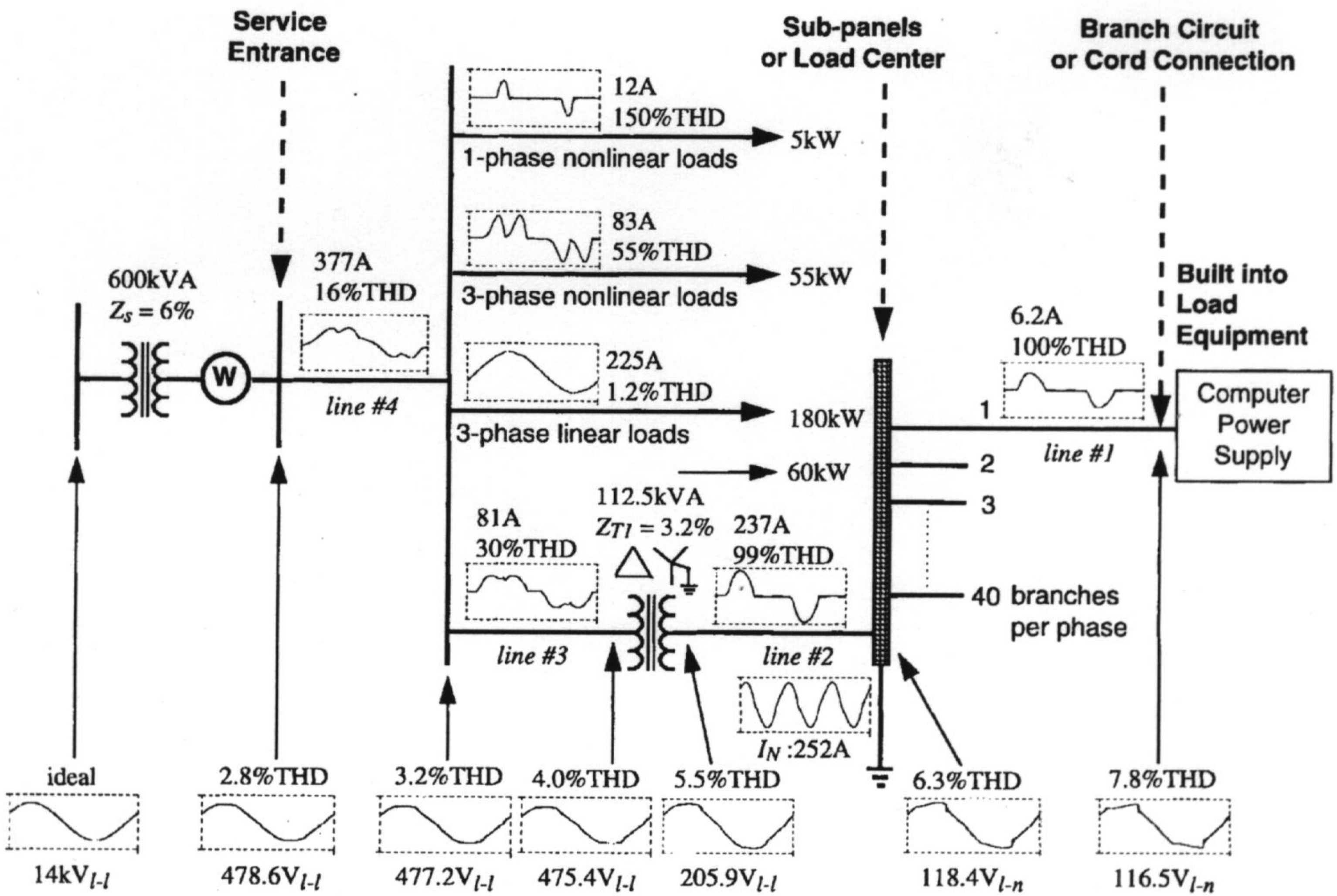
Displacement factor $= \cos\psi_1 = \frac{1}{\sqrt{2}} = 0.707$

Distortion factor $= \frac{I_1}{I} = \frac{20}{\sqrt{600}} = 0.817$

Therefore, the power factor is

$$PF = \frac{1}{\sqrt{2}}\frac{2}{\sqrt{6}} = 0.577$$

Wave Profiles in a Commercial Building



Harmonics Standards

International Electrotechnical Commission (IEC) European Standards.

- EN 61000-3-2 Harmonic Emissions standards were first published as IEC 55-2 1982 and applied only to household appliances. It was revised and reissued in 1987 and 1995 with the applicability expanded to include all equipment with input current $\leq$ 16A per phase. However, until January 1st, 2001 a transition period is in effect for all equipment not covered by the standard prior to 1987.

- The objective of EN 61000-3-2 (harmonics) is to test the equipment under the conditions that will produce the maximum harmonic amplitudes under normal operating conditions for each harmonic component. To establish limits for similar types of harmonics current distortion, equipment under test must be categorized in one of the following four classes.

CLASS-A: Balanced three-phase equipment and all other equipment except that stated in one of the remaining three classes.

CLASS-B: Portable electrical tools, which are hand held during normal operation and used for a short time only (few minutes)

CLASS-C: Lighting equipment including dimming devices.

CLASS-D: Equipment having an input current with special wave shape (e.g.equipment with off-line capacitor-rectifier AC input circuitry and switch Mode power Supplies) and an active input power 600W.

- Additional harmonic current testing, measurement techniques and instrumentation guidelines for these standards are covered in IEC 1000-4-7.

- **IEEE 519-1992 United States Standards on harmonic limits**

  - IEEE limits service entrance harmonics.
  - The IEEE standard 519-1992 limits the level of harmonics at the customer service entrance or Point of Common Coupling (PCC).
  - With this approach the costumer's current distortion is limited based on relative size of the load and the power supplier's voltage distortion based on the voltage level.

  IEEE 519 and IEC 1000-3-2 apply different philosophies, which effectively limit harmonics at different locations. IEEE 519 limits harmonics primarily at the service entrance while IEC 1000-3-2 is applied at the terminals of end-user equipment. Therefore, IEC limits will tend to reduce harmonic-related losses in an industrial plant wiring, while IEEE harmonic limits are designed to prevent interactions between neighbors and the power system.

How to Eliminate Harmonics?

- Preventing harmonic generation for newer systems:
  - High input power factor regulators
  - Switching regulators
  - High pulse number AC/DC converters
- For existing sources of harmonics:
  - Installing filters on DC side of rectifier.
  - Installing filters on AC side.
- Filters can be passive or active; active can be shunt or series!