Harmonics in Metering

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Focus of this Presentation

- Definition and basic theory of harmonics
- What are harmonics as they relate to electric power?
- What are some common sources of harmonics in electronics?
- How do these harmonics affect metering and other equipment in power distribution and measurement?

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Harmonics – What are they?

- Mathematical definition of a harmonic is "a component frequency of the signal that is an integer multiple of the fundamental frequency."
- In North America:
  - The fundamental frequency is 60 Hz
  - Integer multiples would be
    - 2nd harmonic - 2 x 60 = 120 Hz
    - 3rd harmonic – 3 x 60 = 180 Hz
    - 4th harmonic – 4 x 60 = 240 Hz

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Harmonics Theory

- Basic Harmonic Theory
  - Harmonics describe disturbances which repeat every cycle for a significant number of cycles
- Engineers use Fourier notation to describe harmonic waveforms

$$V(t) = \sqrt{2}\sum_{n=1}^{\infty}\left(V_n Sin(n\omega_0 t - \alpha_n)\right)$$

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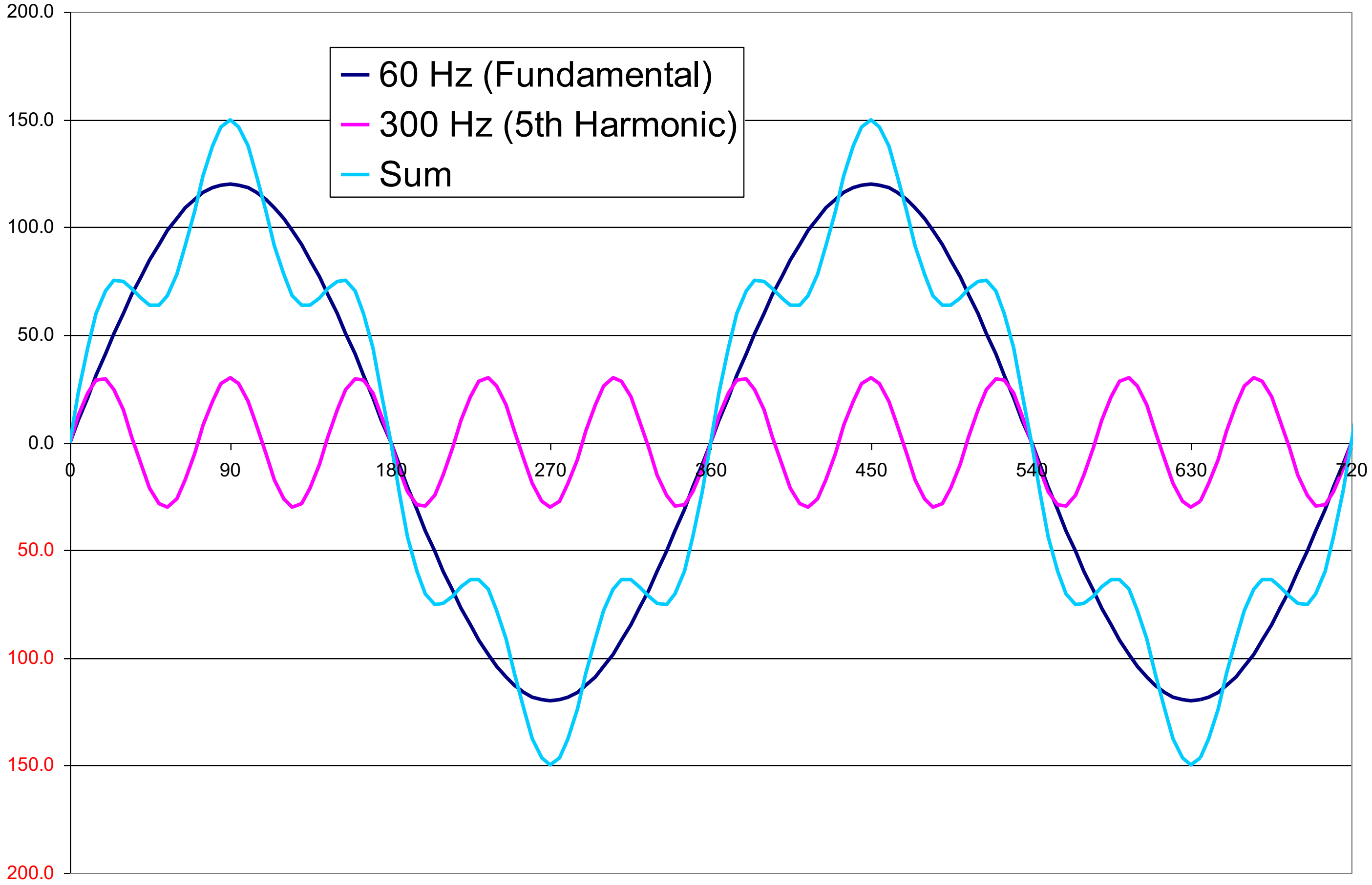
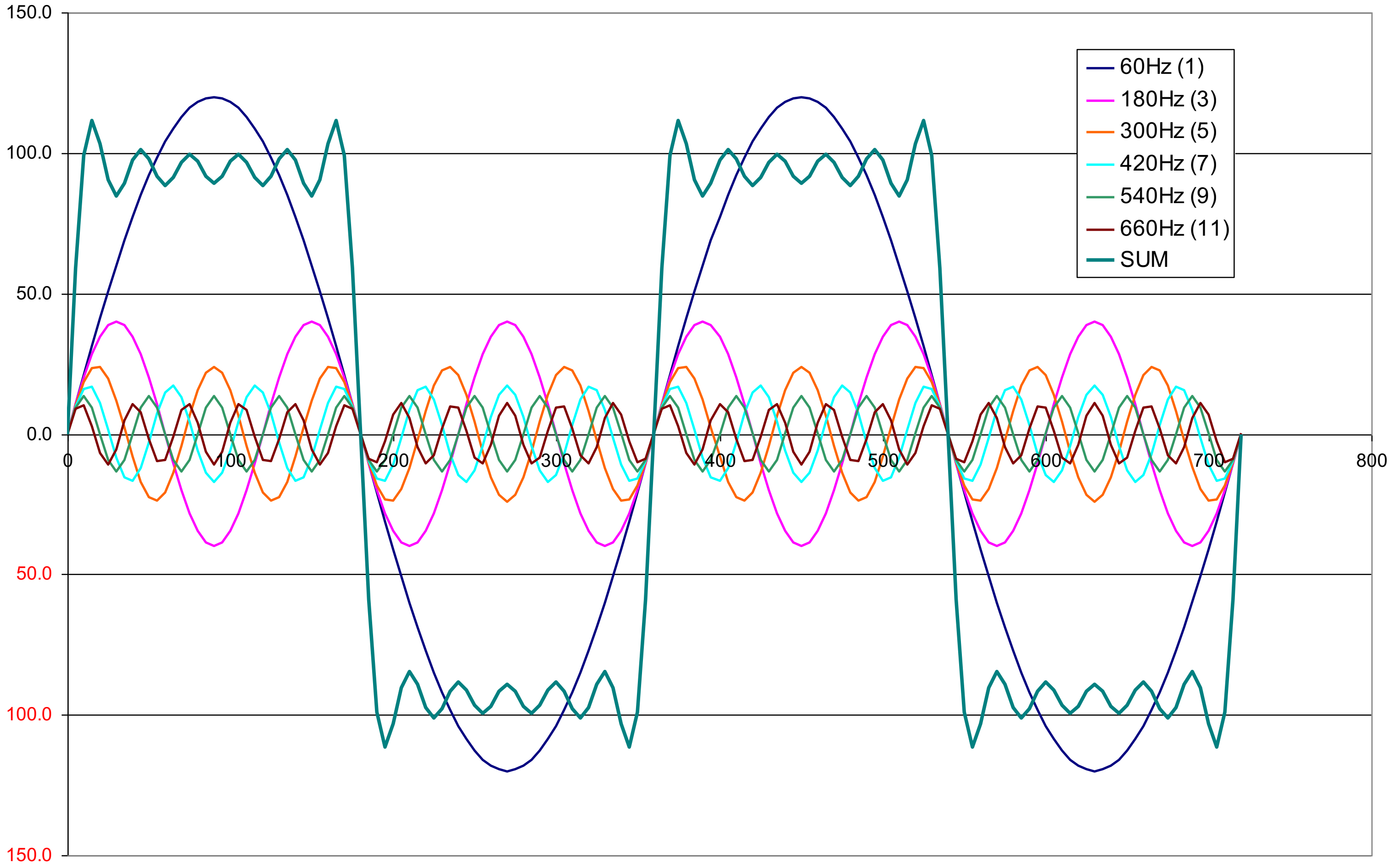
Harmonics Theory



$$V(t) = \sqrt{2}\sum_{n=1}^{\infty}\left(V_n Sin(n\omega_0 t - \alpha_n)\right)$$

Harmonics Theory



Even a square wave can be represented as a series of harmonics.

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Harmonics in Power

- Repetitive contamination of the voltage or current waveform
- Generated by non-linear loads. Voltage harmonics are a reflection of the non-linear load on a distribution system with finite impedance
- Produce a variety of infrastructural problems
- Generate system losses
- Can result in metering errors and disputes

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Harmonics – what aren't they?

- Sags, dips, swells
- Transient voltages
- Frequency variations

These are all non-periodic kinds of power quality issues. Harmonics MUST be periodic, meaning they occur at a given interval.

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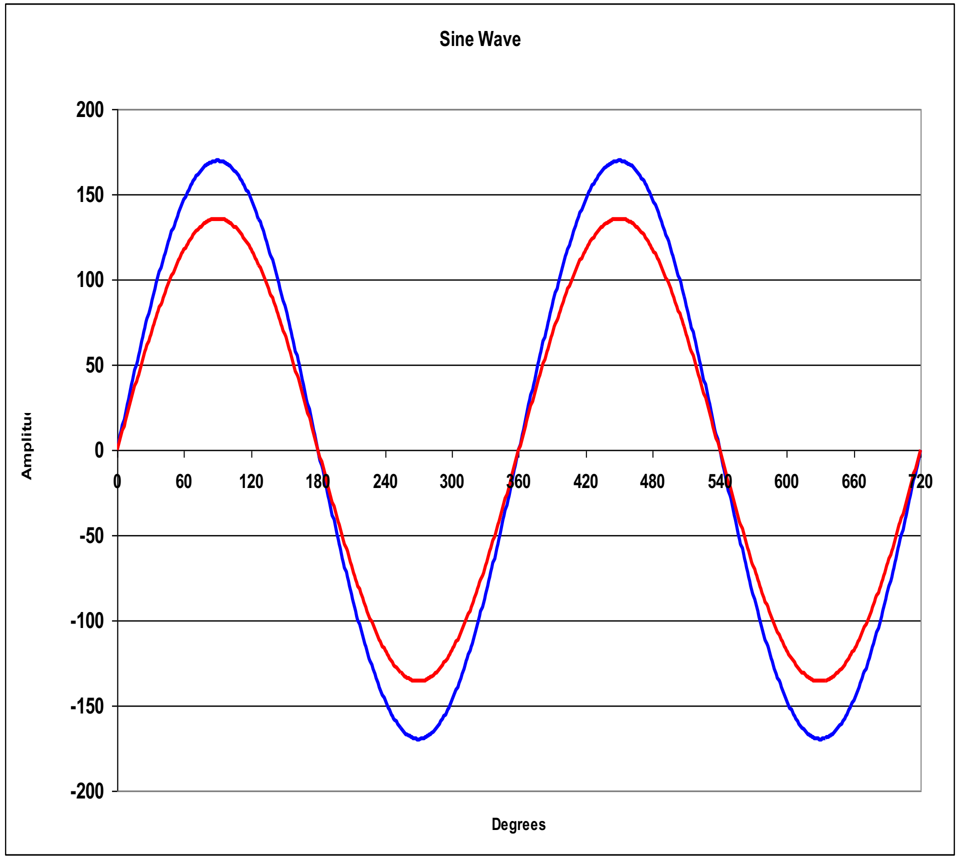
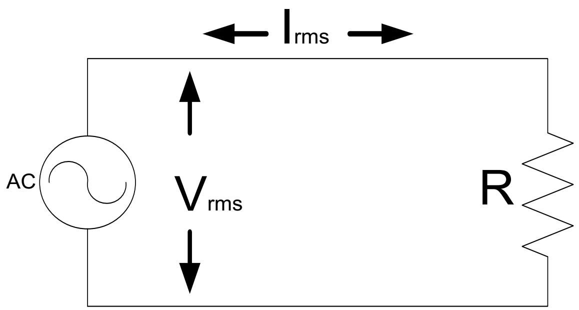
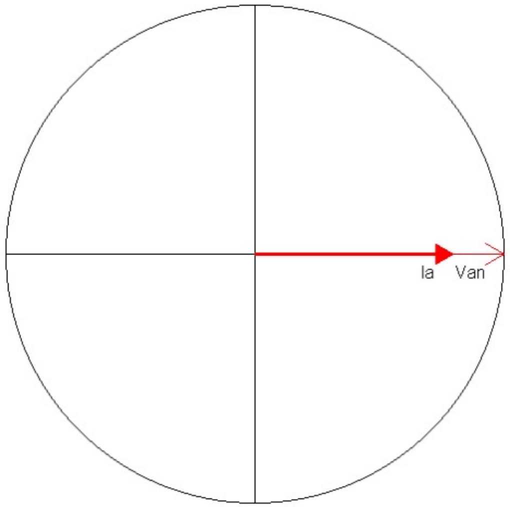
Focus on Harmonics

- Where do harmonics come from?
  - Non-linear loads at the customer's site
  - Coupling from loads at other sites sharing the distribution system
    - One customer's harmonic current load is converted into voltage harmonics at other customer's sites by the impedance of the system

Linear Load – Resistive

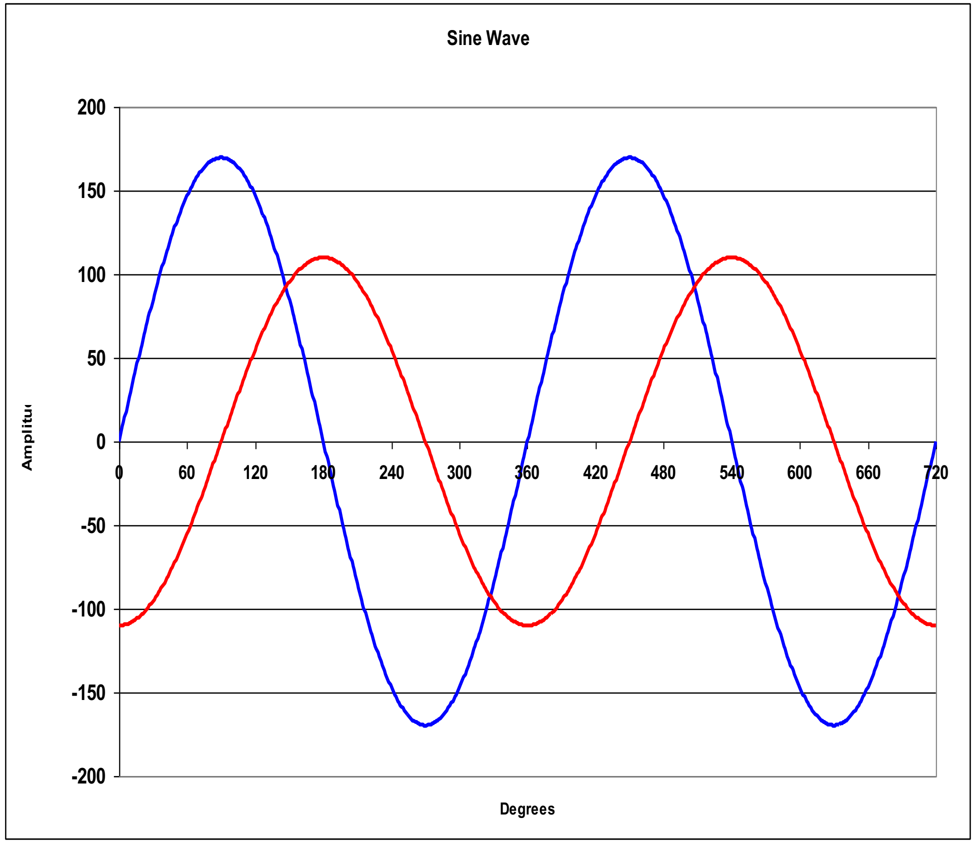


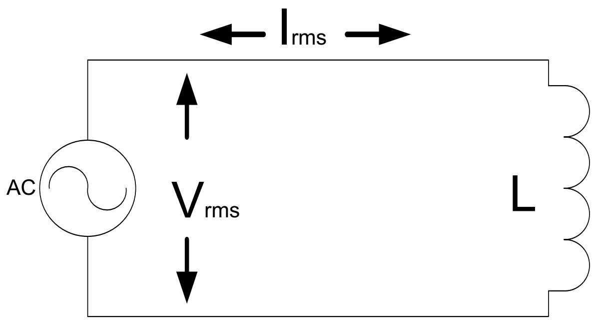


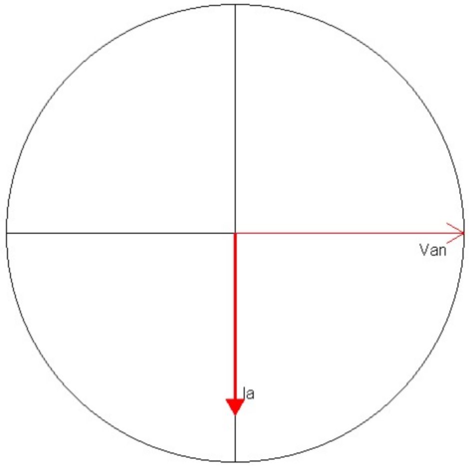


Resistors are measured in Ohms. When an AC voltage is applied to a resistor, the current is in degrees. A resistive load is considered a "linear" load because when the voltage is sinusoidal the current is sinusoidal.

Linear Load – Inductive

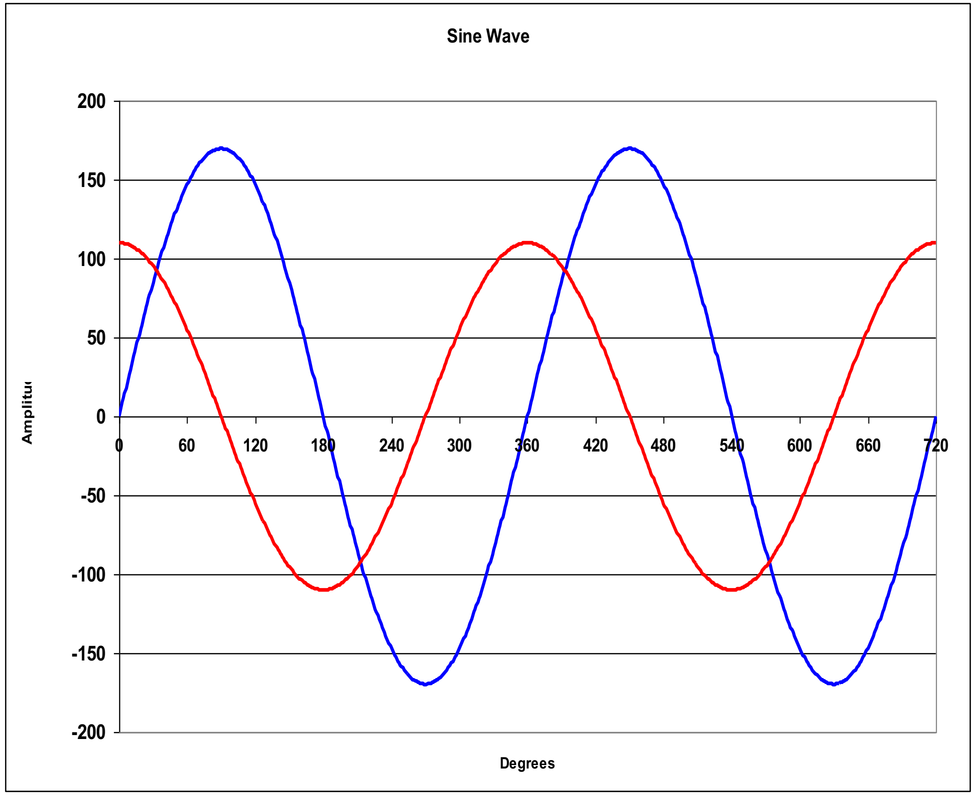


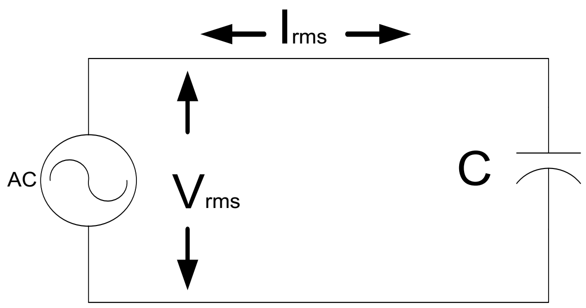


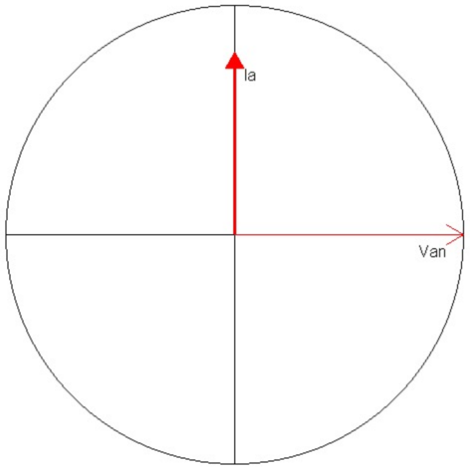


Inductors are measured in Henries. When an AC voltage is applied to an inductor, the current is 90 degrees out of phase. We say the current "lags" the voltage. A inductive load is considered a "linear" load because when the voltage is sinusoidal the current is sinusoidal.

Linear Load – Capacitive







Capacitors are measured in Farads. When an AC voltage is applied to a capacitor, the current is 90 degrees out of phase. We say the current "leads" the voltage. A capacitive load is considered a "linear" load because when the voltage is sinusoidal the current is sinusoidal.

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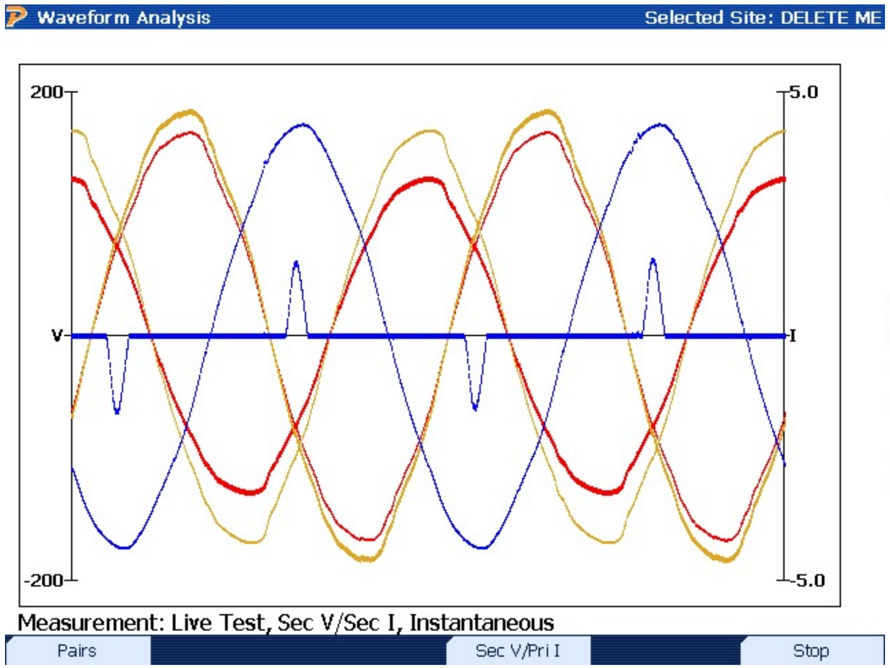
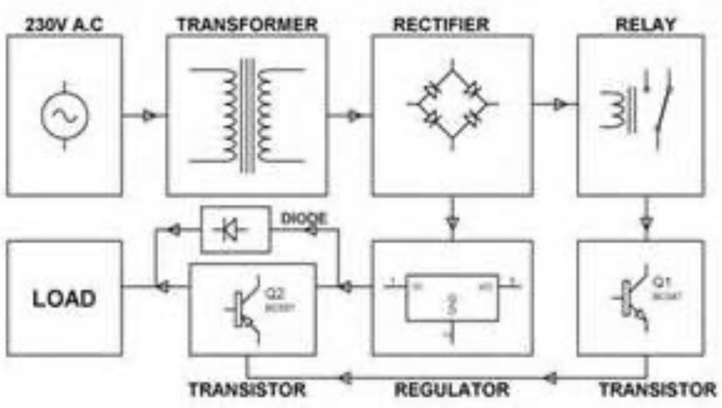
Non-Linear Load – Switching Power Supply





An AC-DC switching power supply is an example of a non-linear load. The circuit uses a diode and switch (normally a transistor or relay) which produces a non-sinusoidal effect on the current as seen in the waveform above.

Total Harmonic Distortion (THD)

THD is a measurement of the ratio of the sum of the harmonic power to the power of the fundamental frequency.

$$\mathrm{THD} := \frac{\sqrt{\sum_{n=2}^{4} (V_n)^2}}{V_1}$$

This is an equation for a waveform with 3 harmonics.
V_1 is the fundamental (60Hz)
V_2 is the 2nd harmonic (120Hz)
V_3 is the 3rd harmonic (180Hz)
V_4 is the 4th fundamental (240Hz)

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Total Harmonic Distortion (THD)

EXAMPLES

Fundamental signal (60 Hz) is 10A
2nd harmonic (120 Hz) is 0.3A
3rd harmonic (180 Hz) is 0.2A
4th harmonic (240 Hz) is 0.1A
THD = 3.7%

Fundamental signal (60 Hz) is 12A
2nd harmonic (120 Hz) is 10A
3rd harmonic (180 Hz) is 3A
4th harmonic (240 Hz) is 1.5A
THD = 87.9%

It is possible for THD to be greater than 100%, meaning that the signal has more harmonic energy than fundamental energy!

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Past Harmonic Sources

SOURCE	TYPE	LEVEL
Transformer ▪ Saturation ▪ Energization	Current Harmonics 3,5,7… & 2,4…	1 to 85%
Arc Furnace Welders	Voltage Harmonics 5 & 7	2.5 to 8%
Line Commutated Converters	Volt. & Cur. Harmonics H = np ± 1	10 to 30%
Static VAR Compensators	Current Harmonics H = np ± 1	2 to 4%
Saturable Reactors	Current Harmonics 3,5,7…	1 to 8%

New Harmonic Sources

SOURCE	TYPE	LEVEL
Fluorescent Lighting	Current Harmonics 3,5,7… up to > 49	> 400%
Electronic Power Supplies Especially Computers	Current Harmonics 3,5,7… up to > 25	>100%

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Are Newer Light Bulbs "green"?

- Big push now underway to move to "green" light bulbs such as CCFL and LED in place of incandescent
- CCFLs and LEDs consume lower W and VA overall for a comparable amount of light

EXCEPT…

- They generate VARs and a high level of harmonics!

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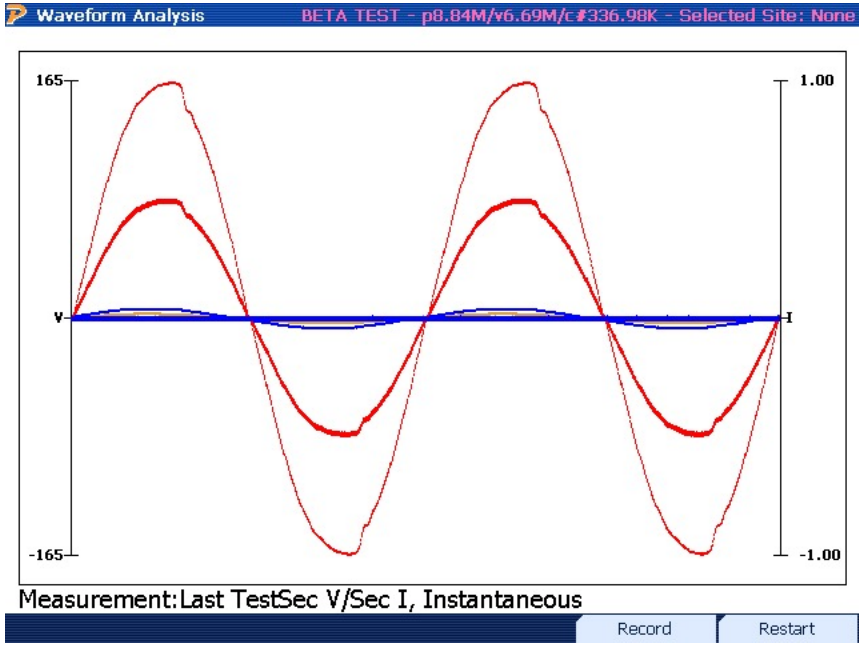
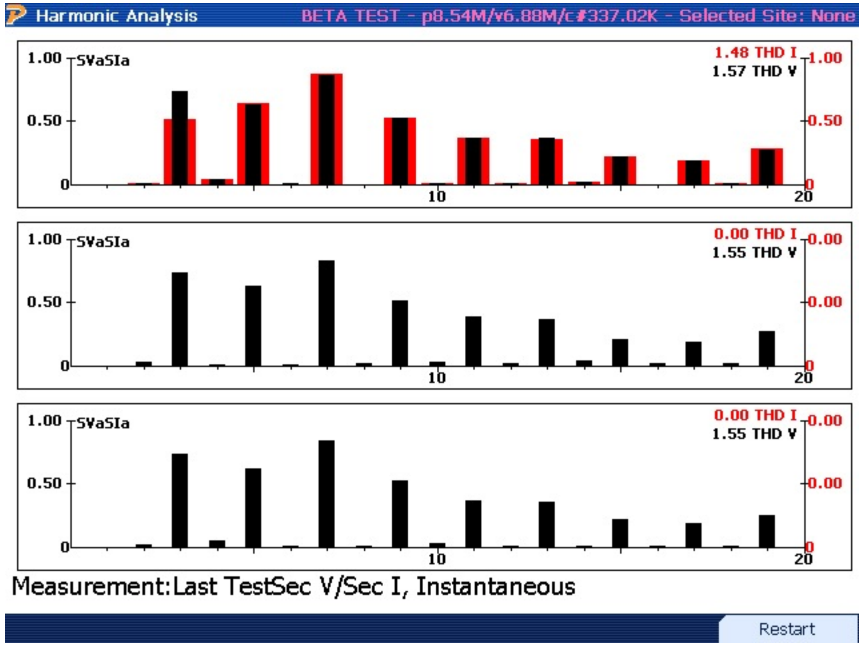
Green 60W Incandescent Bulb





Active Power = 41W

Reactive Power = <1 VAR

Apparent Power = 41VA

Current THD = 1.5%

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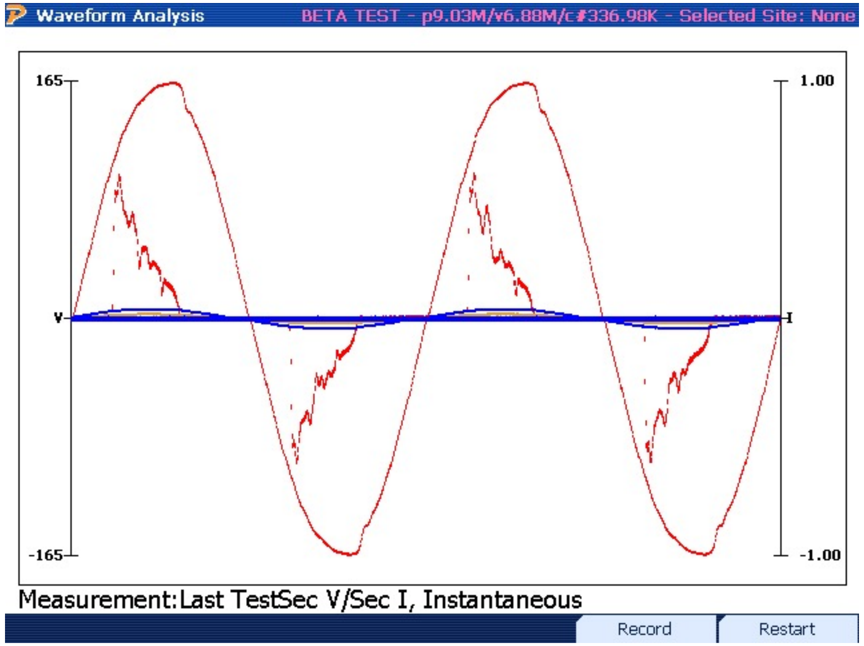
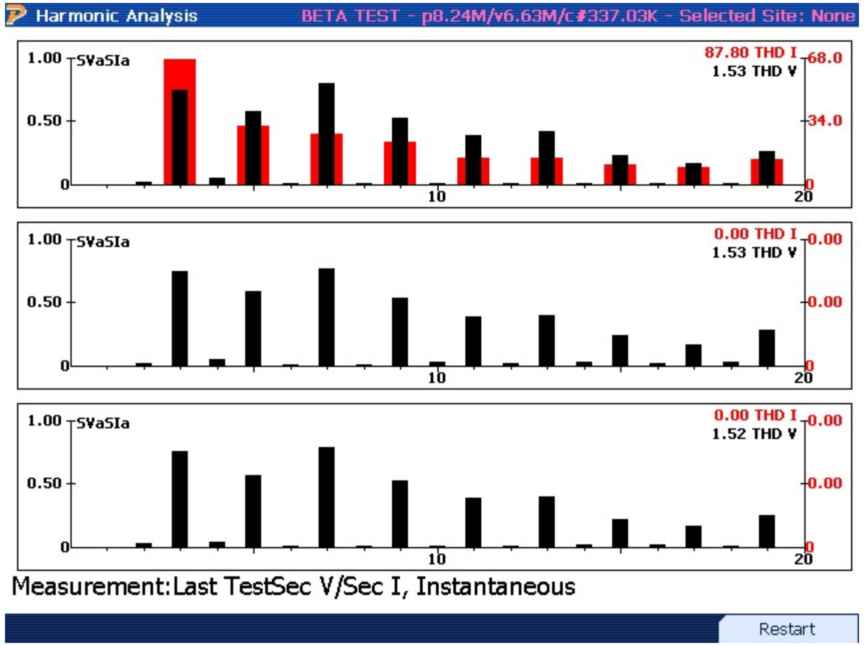
60W Equivalent CCFL Bulb





Active Power = 14 W

Reactive Power = 6 VAR

Apparent Power = 16 VA

Current THD = 88%

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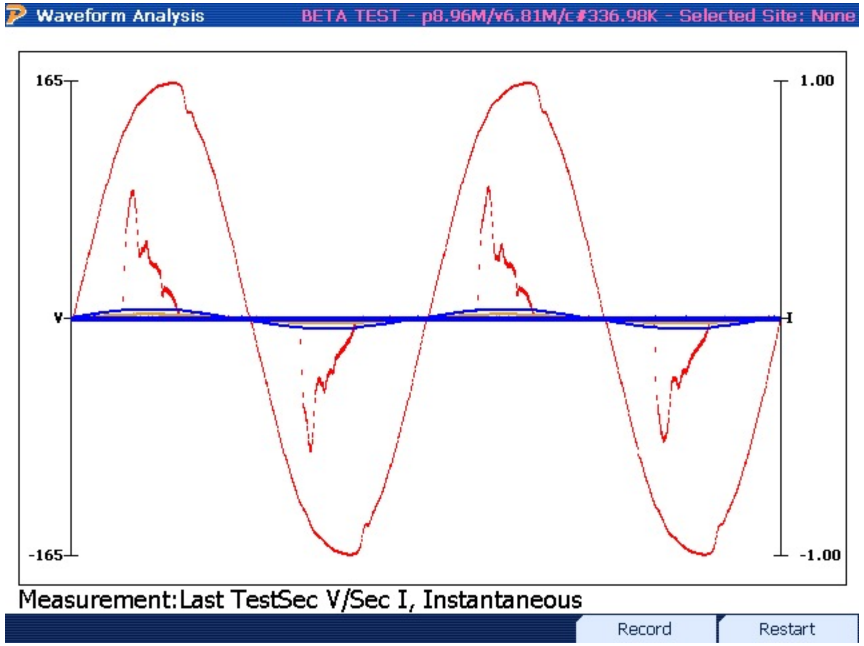
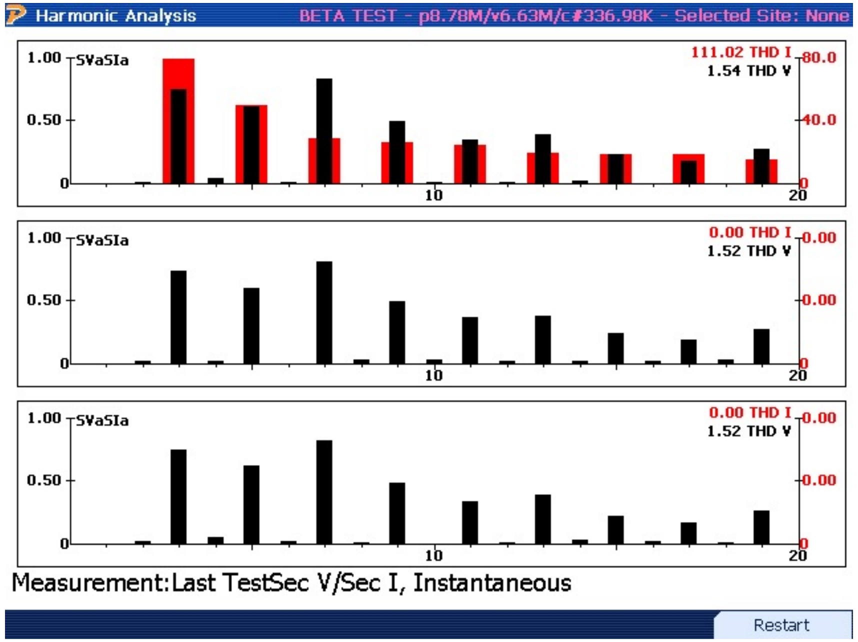
60W Equivalent LED Bulb





Active Power = 11 W

Reactive Power = 4 VAR

Apparent Power = 12 VA

Current THD = 111%

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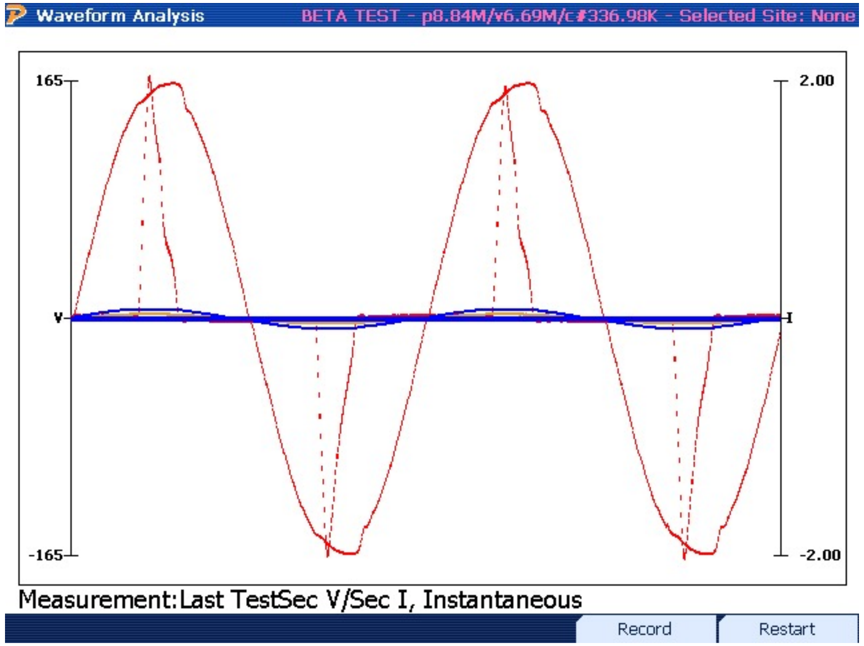
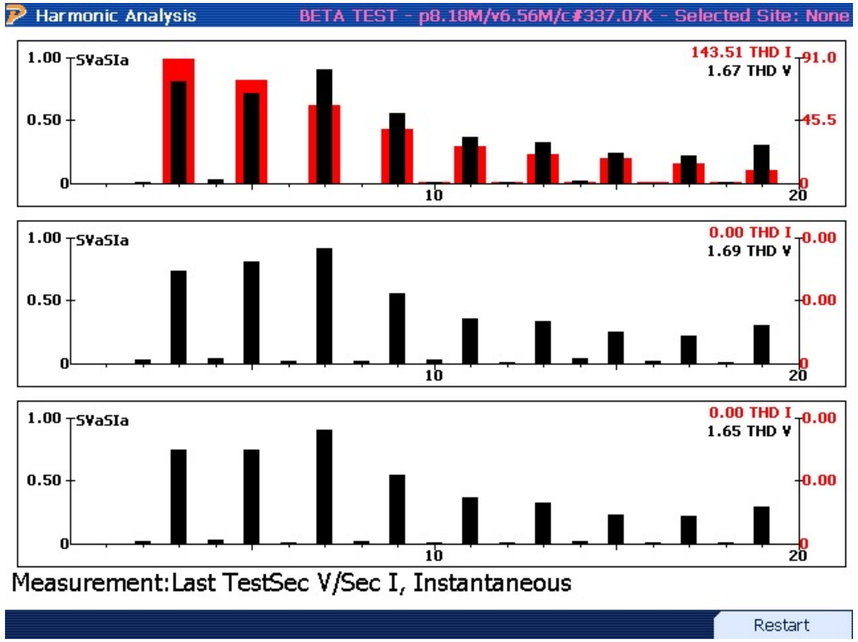
Laptop Computer Power Supply





Active Power = 35 W

Reactive Power = 6 VAR

Apparent Power = 37 VA

Current THD = 144%

Harmonic Theory
An Alternate Approach

- Harmonics can be grouped into “sequences” which help us understand their effects.

Name	F	2nd	3rd	4th	5th	6th	7th	8th	9th
Freq	60	120	180	240	300	360	420	480	540
Seq	+	-	0	+	-	0	+	-	0

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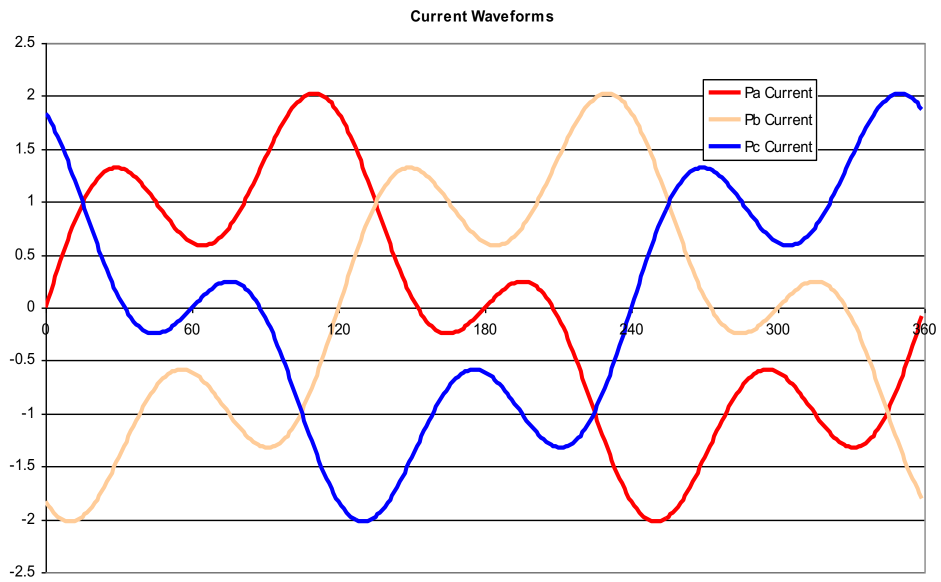
Harmonic Theory
An Alternate Approach

Name	F	2nd	3rd	4th	5th	6th	7th	8th	9th
Freq	60	120	180	240	300	360	420	480	540
Seq	+	-	0	+	-	0	+	-	0



Positive (+)

- If fundamental rotation is ABC then positive (+) sequence harmonics have ABC rotation

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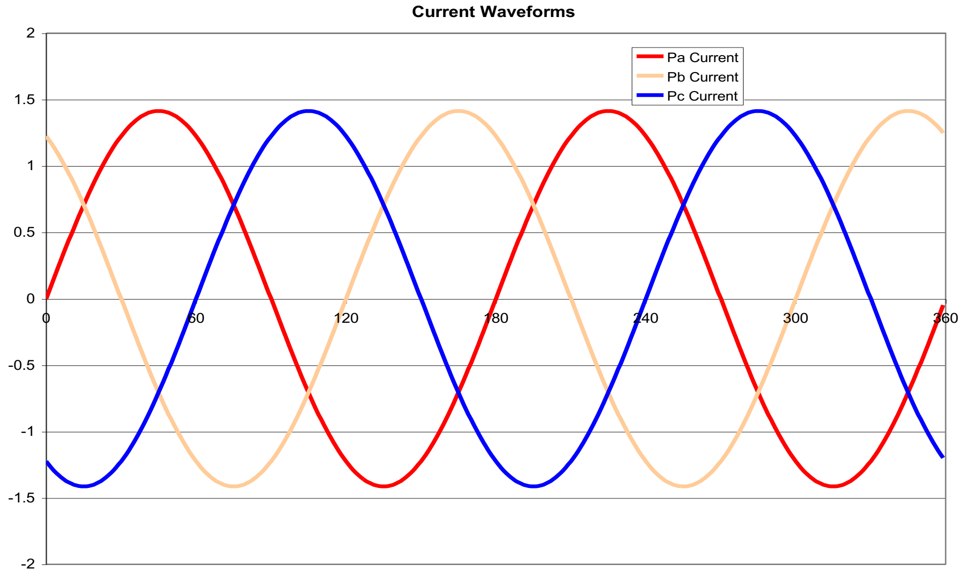
Harmonic Theory
An Alternate Approach

Name	F	2nd	3rd	4th	5th	6th	7th	8th	9th
Freq	60	120	180	240	300	360	420	480	540
Seq	+	-	0	+	-	0	+	-	0

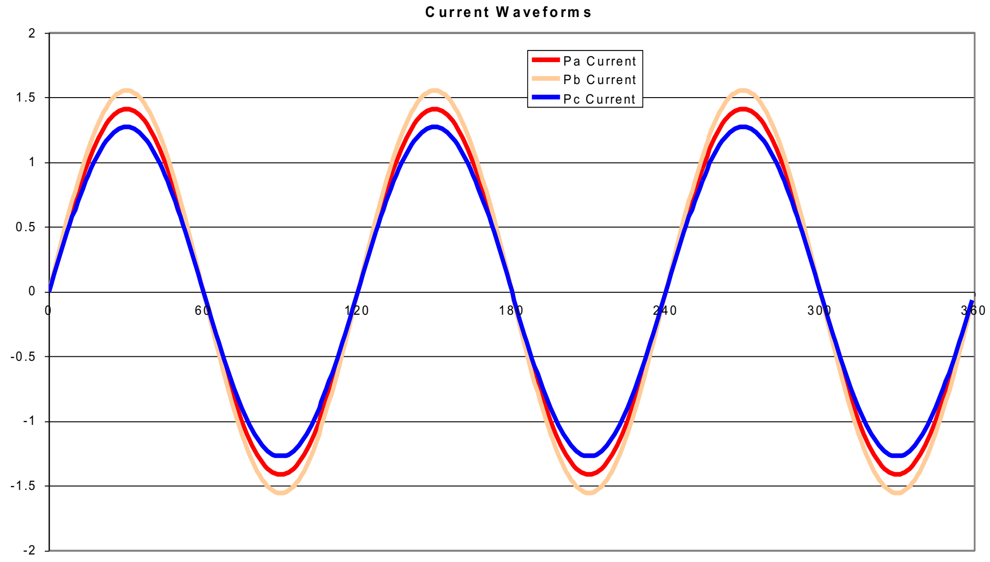


Negative (-)

- If fundamental rotation is ABC then negative (-) sequence harmonics have CBA rotation

Harmonic Theory
An Alternate Approach

Name	F	2nd	3rd	4th	5th	6th	7th	8th	9th
Freq	60	120	180	240	300	360	420	480	540
Seq	+	-	0	+	-	0	+	-	0



ZERO (0)

- If fundamental rotation is ABC then zero (0) sequence harmonics have NO rotation

Harmonic Theory
An Alternate Approach

- Positive (+)
  - Heating of conductors and transformers
- Negative (-)
  - Heating of conductors and transformers
  - Tries to make motors run backwards
- Zero (0)
  - Results in neutral currents which can be larger than phase currents

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How do harmonics affect metering?

- Mechanical meters will not register harmonics well – 80% error at higher harmonics
- Solid state meters can measure harmonics well depending on the sampling rate and VAR calculation used
- CTs and PTs can only pass a limited range of harmonics

Harmonics & Metering Accuracy

- Primarily affect the calculation of VA, VAR and Power Factor
  - No ANSI standard for these calculations at this time
  - Different manufacturers use different methods and definitions.
  - Most manufacturers allow the user to make several choices for each
  - Differences of over 50 percent in answers can occur in high harmonic situations

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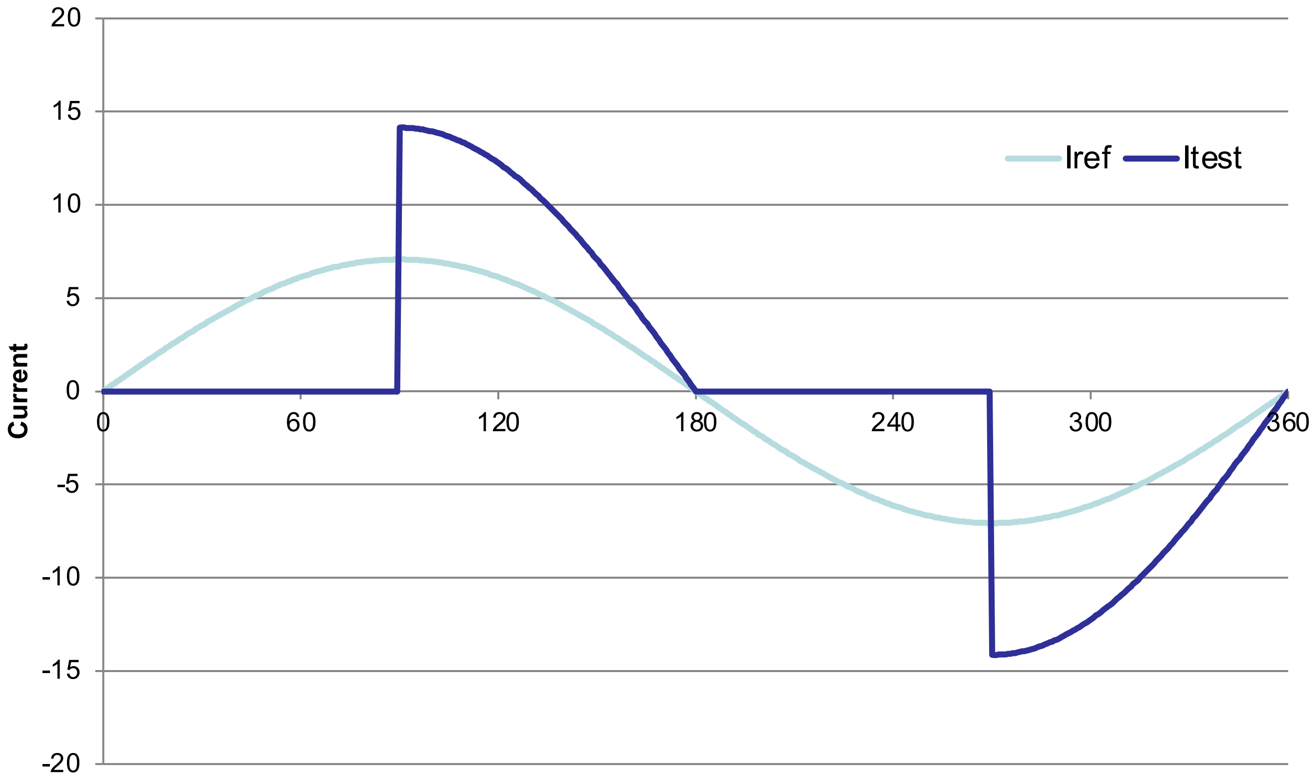
Harmonics & Metering Accuracy



Waveform #1 - 90 Degree Phased Fired Waveform
Typical for a light dimmer set to 50%

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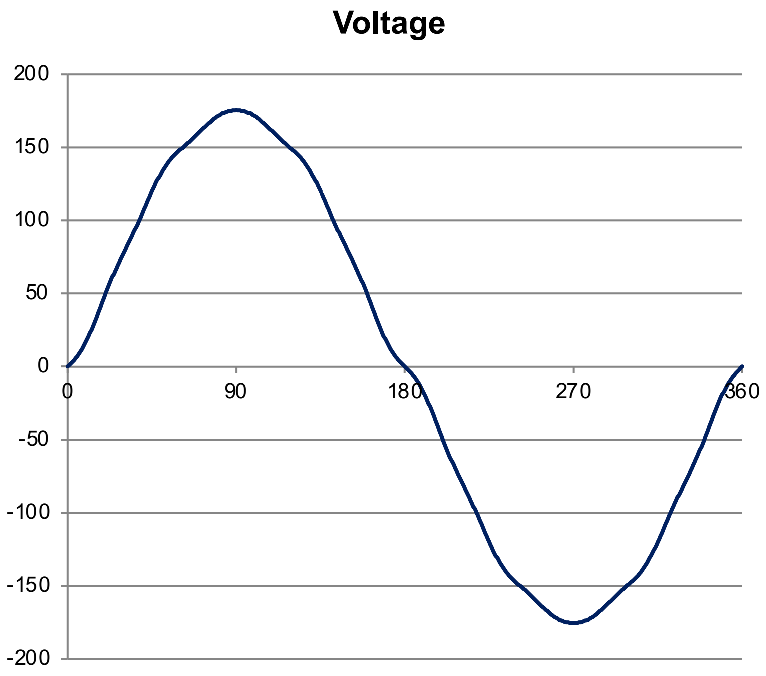
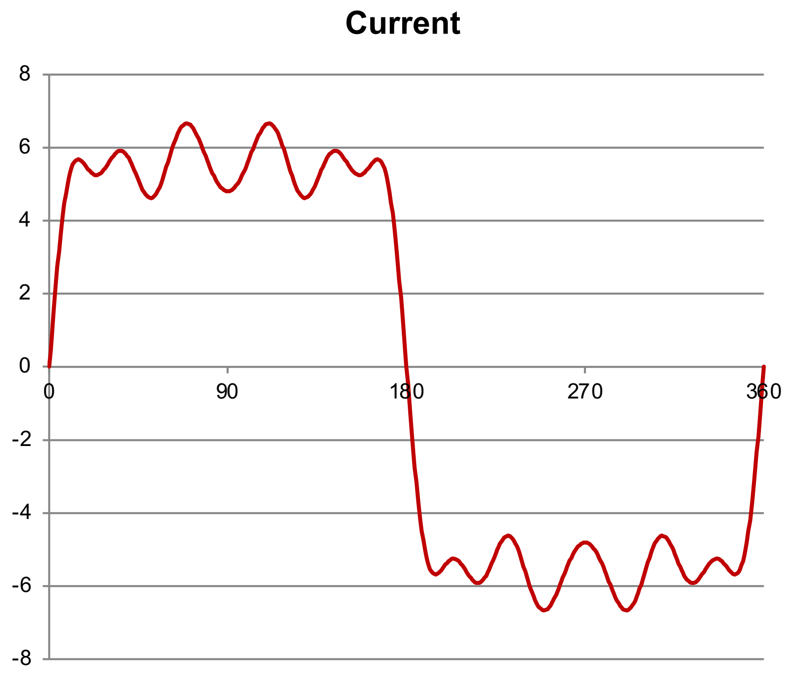
Harmonics & Metering Accuracy





Waveform #2 - Quadriform Waveform
Switched Load Device

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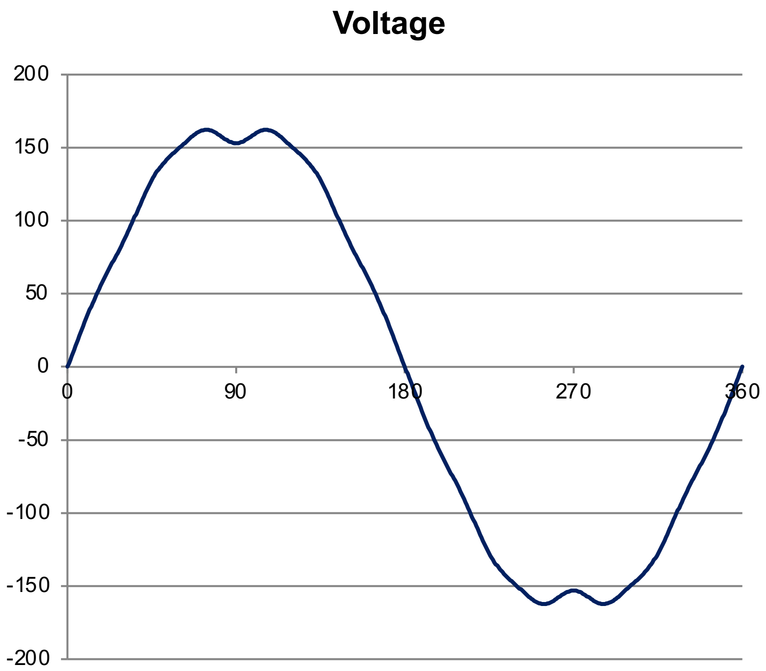
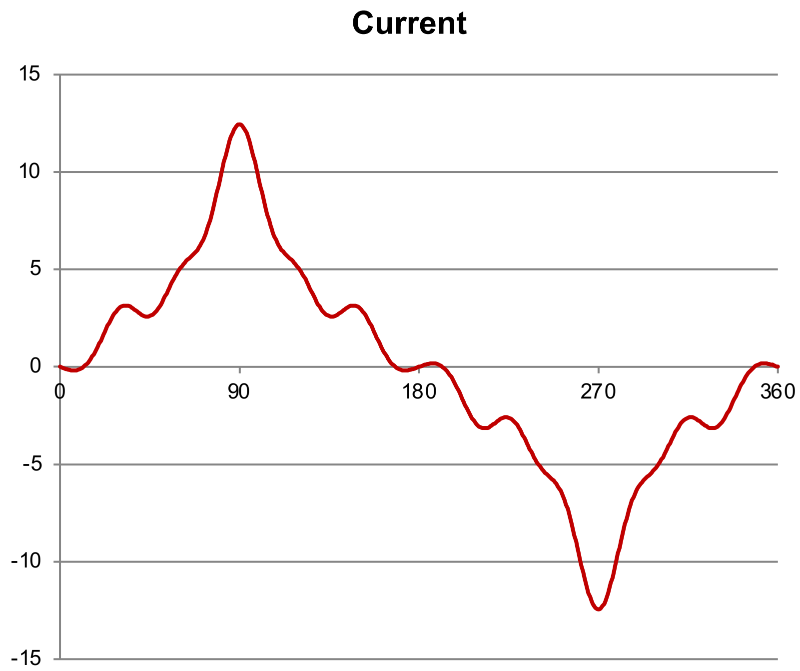
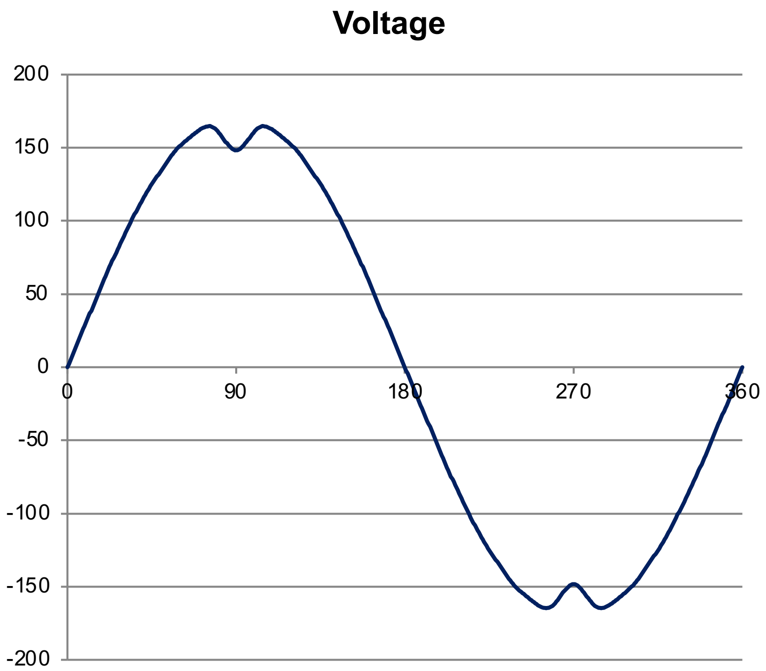
Harmonics & Metering Accuracy

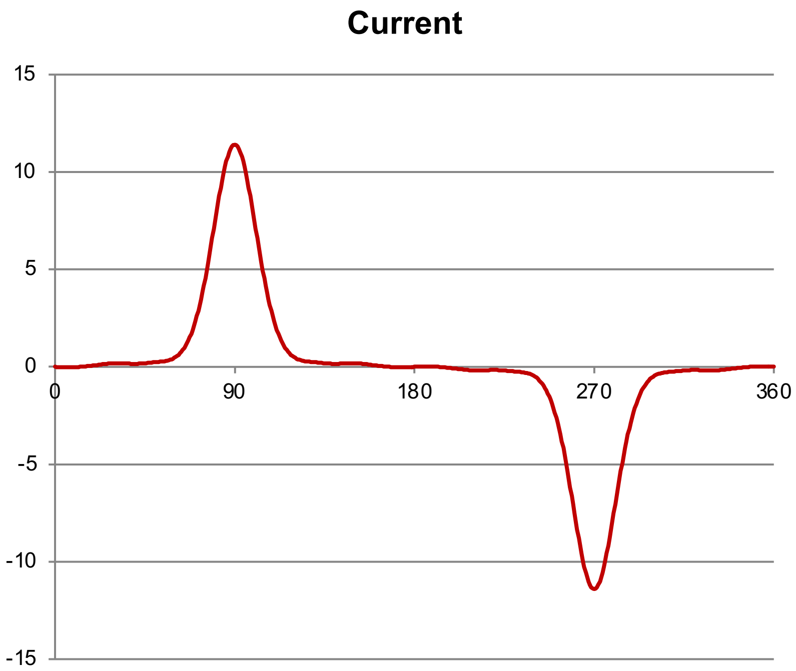




Waveform #3 - Peaked Waveform
Switching Power Supply

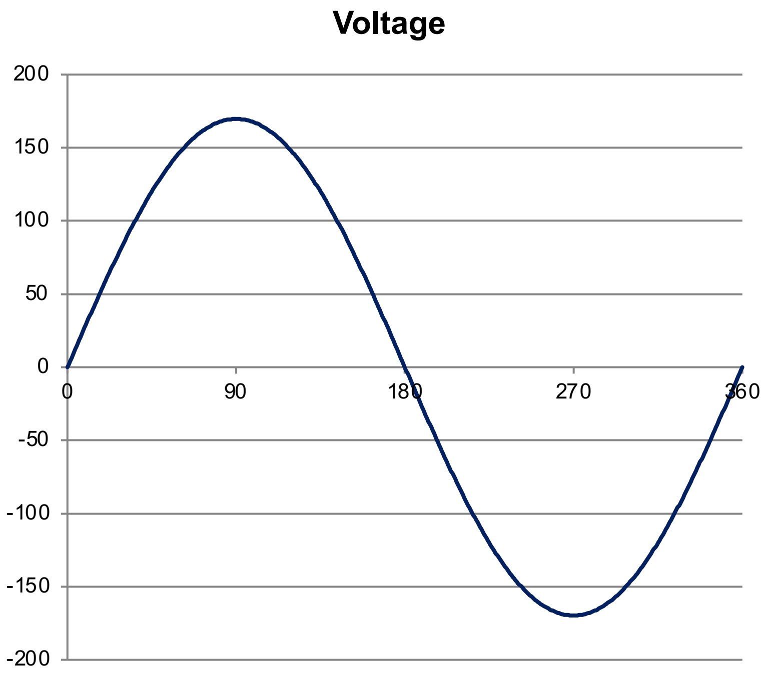
Harmonics & Metering Accuracy

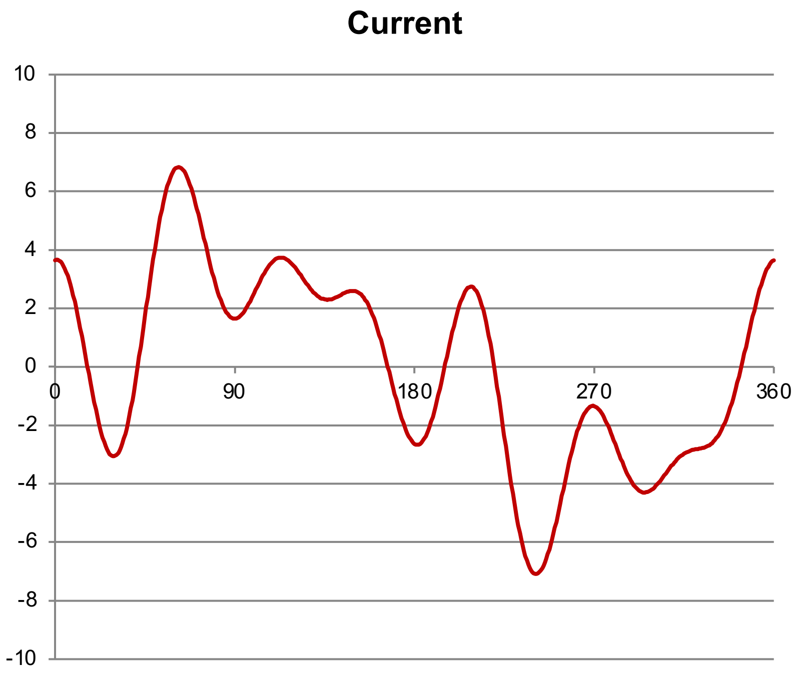




Waveform #4 - Pulse Waveform
Switching Power Supply

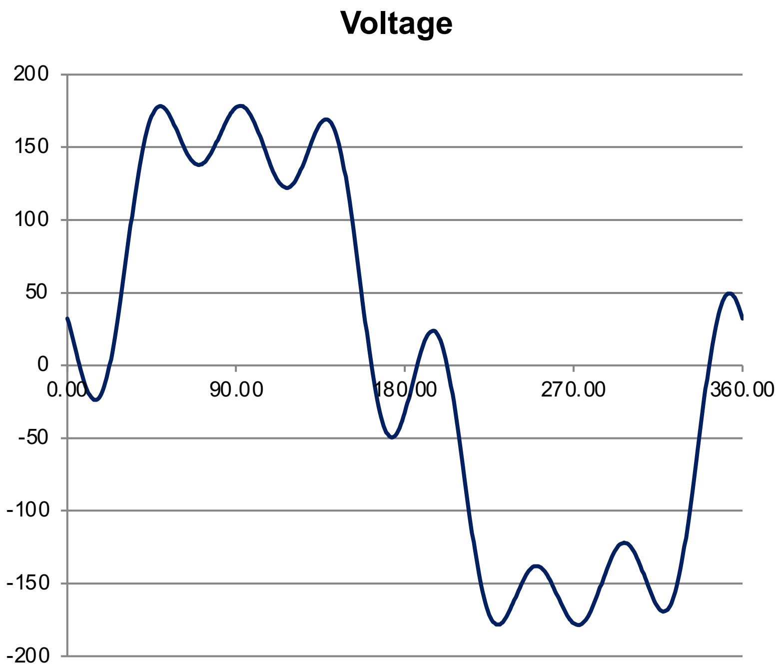
Harmonics & Metering Accuracy

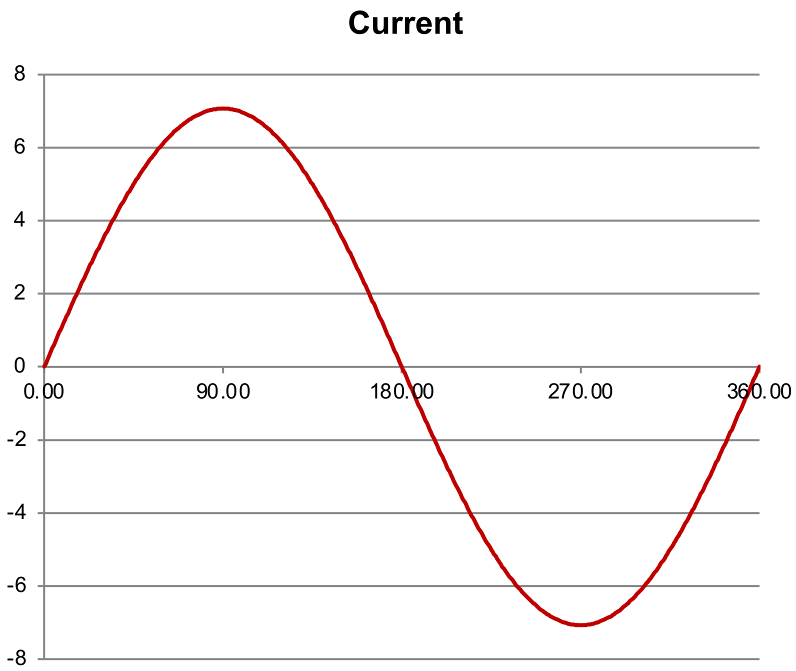




Waveform #5 – Multiple Zero Crossing Current Waveform

Harmonics & Metering Accuracy





Waveform #6 – Multiple Zero Crossing Voltage Waveform

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Harmonic Compensation

- Harmonics can be compensated for at the customer's facility
- Solution must be tailored to the problem
- Examples of solutions:
  - Active Filter – mirror image of harmonic
  - Tuned Filter – effective but expensive
  - Zig zag transfomer reduces 3rd harmonics in neutral
- There is no "one size fits all" solution

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IEEE Power Quality Standards

- SCC-22 Power Quality Standards Coordinating Committee
- 1159: Monitoring Electric Power Quality
  - 1159.1: Guide for Recorder and Data Acquisition Requirements
  - 1159.2: Power Quality Event Characterization
  - 1159.3: Data File Format for Power Quality Data Interchange
- P1564: Voltage Sag Indices
- 1346: Power System Compatibility with Process Equipment
- P1100: Power and Grounding Electronic Equipment
- 1433: Power Quality Definitions
- P1453: Voltage Flicker
- 519: Harmonic Control in Electrical Power Equipment
- P519A: Guide for Applying Harmonic Limits on Power Systems

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IEC Power Quality Standards

- 61000-1-X Definitions and methodology
- 61000-2-X Environment
- 61000-3-X Limits
- 61000-4-X Test and measurements
- 61000-5-X Installation and mitigation
- 61000-6-X Generic immunity and emissions standards
- Working Groups and Committees
  - SC77A Low Frequency EMC Phenomena
  - TC77/WG1 Terminology
  - SC77A/WG1 Harmonics and other low frequency disturbances
  - SC77A/WG6 Low frequency Immunity Tests
  - SC77A/WG2 Voltage fluctuations and other low frequency disturbances
  - SC77A/WG9 Power Quality measurement methods

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