ECE 528 – Understanding Power Quality

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

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Lecture 9

Today: Harmonic fundamentals

FPQ chapters 6 and 7, PSQ chapters 5 and 6

- Background and sources
- How current distortion creates voltage distortion
- Harmonic impacts – general principals
- Power system quantities with harmonics
- Harmonic Indices
- Harmonic phase sequence
- Triplen harmonics
- Harmonic sources

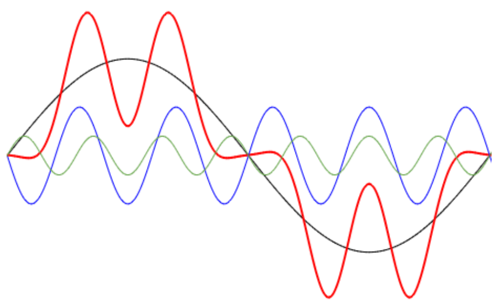
References:
[1] "Fundamentals of Electric Power Quality" by Surya Santoso
[2] "Harmonics and how they relate to Power Factor", W. Mack Grady and Robert J. Gilleskie, 1993 http://users.ece.utexas.edu/~grady/POWERFAC.pdf

Text updates

- Both texts mention IEEE-519-1992: *IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.*
- The latest version of this standard is IEEE-519-2022: *IEEE Standard for Harmonic Control in Electric Power Systems*.
  - **Get a copy of this standard from the IEEEXplore site via the UI library web site. We'll be using it.**

Harmonics: a mathematical tool

- Power systems are frequency-dependent
- Any periodic waveform can be broken down into its harmonic components
- Finding a waveform's "spectrum" lets us analyze the system one frequency at a time
- We let power analyzers or similar tools find the spectrum for us



Net current = 1st + 5th + 7th

$$X_C = \frac{1}{2\pi f C} \qquad Z_C = -jX_C \qquad C = farads$$

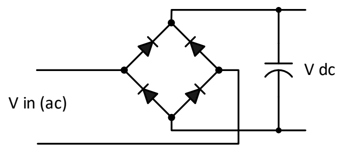
$$X_L = 2\pi f L \qquad Z_L = jX_L \qquad L = henries$$

$$f = freq. (Hz)$$

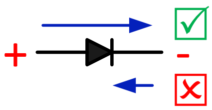
Harmonic Sources: Rectifier-based loads

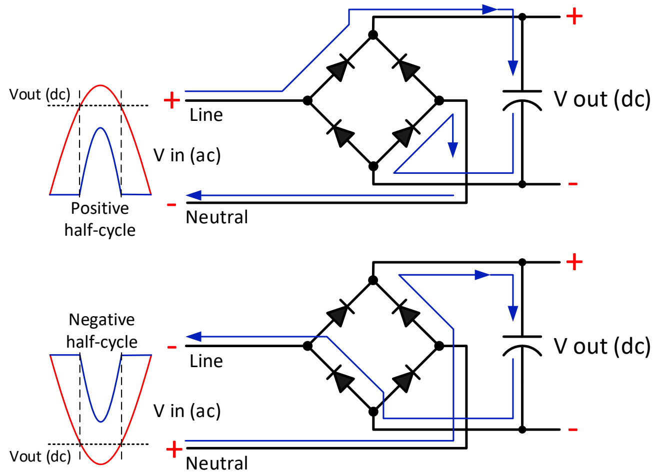
(review from lecture 3)

The basic rectifier with capacitor



Diodes: like one-way valves for current





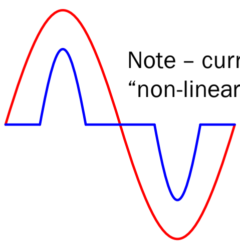
Current flows on source side when Vin > Vout

Harmonic sources: Rectifier-based loads

(review from lecture 3)

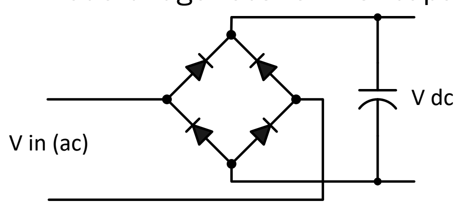
Input AC Voltage

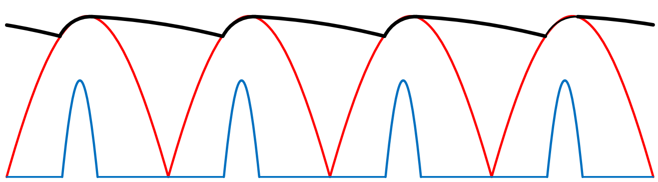
Input AC Current



Note – current is "non-linear"

Diode-bridge rectifier with capacitor





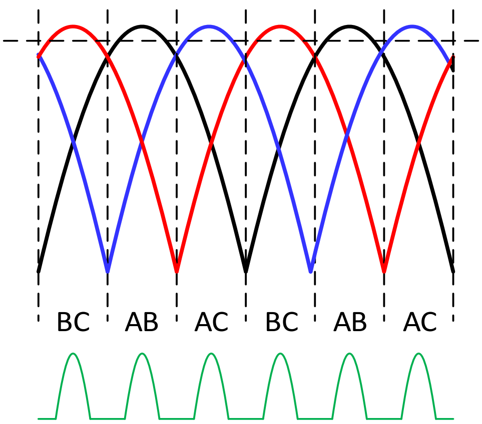
DC Voltage

Rectified Voltage

Current between rectifier and capacitor

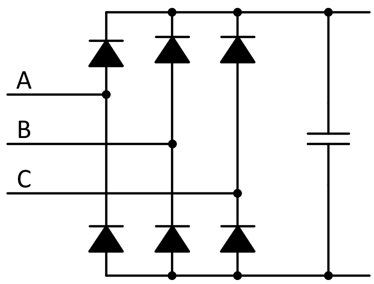
Harmonic sources: 3-Phase rectification

Line-to-line voltages

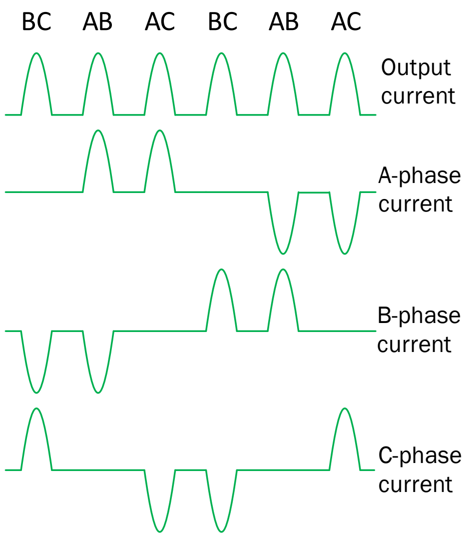


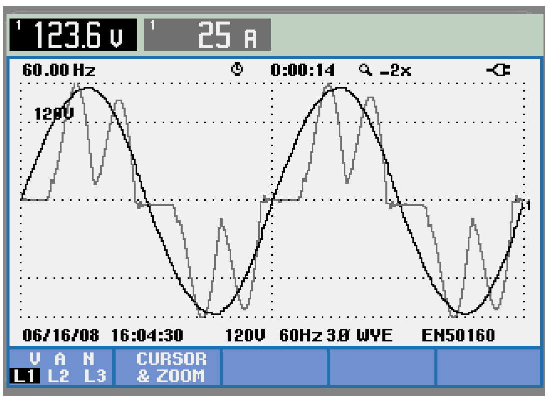
Rectifier output current

- Rectifier connected line-to-line
- Only the pair of phases with the highest line-to-line voltage conducts at any given time



Harmonic sources: 3-Phase rectification





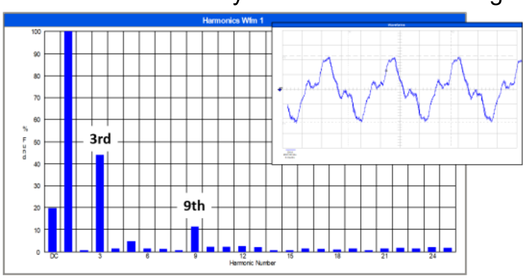
Voltage and current on one phase at a 3-phase variable frequency drive

Characteristic harmonics

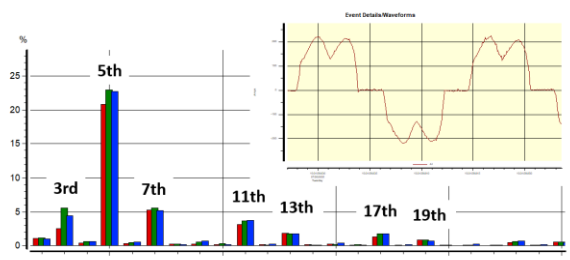
- Significant even harmonics are rare
  - Usually means there is a half wave rectifier in use, or a rectifier has a diode that has failed open
- Single-phase loads tend to produce harmonics that are odd multiples of three (3^{rd}, 9^{th}, 15^{th},…)
- Three-phase loads tend to produce harmonics that satisfy 6n+/-1 where n is 1, 2, 3… (5^{th}, 7^{th}, 11^{th}, 13^{th},…)

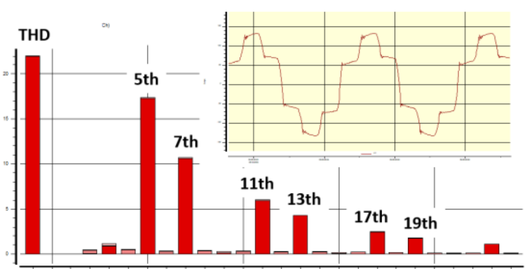
Characteristic harmonic current:

Residence with mostly electronic loads running



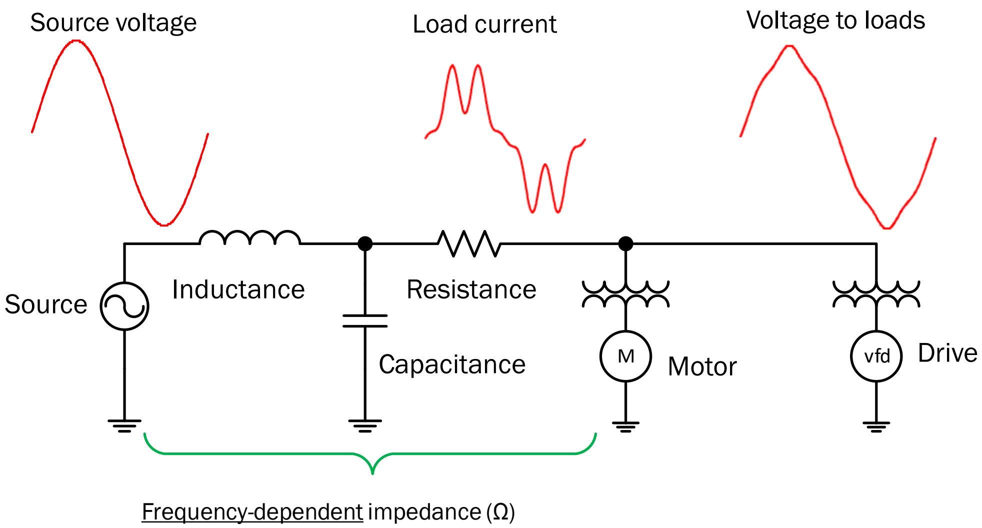
3-phase variable frequency drive





Commercial radio station transmitter
(Power supply uses inductance instead of capacitance to store energy)

How distorted current creates distorted voltage



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Harmonic impacts – general principals:

- Physical impacts tend to be chronic rather than acute
  - Increased heating
    - May cause nuisance operation of fuses, circuit-breakers
  - Reduced equipment lifespan
  - Reduced system capacity
  - Transformers may need to be derated
  - Reduced voltage sag ride through in power supplies
    - Due to “flat-topping”
  - Resonance issues
- Economic impacts
  - Over sizing equipment & conductors
  - Shortened equipment life
  - Losses & inefficiencies

For more on how increased operating temperature reduces the lifespan of components read about the use of the Arrhenius equation in product testing.

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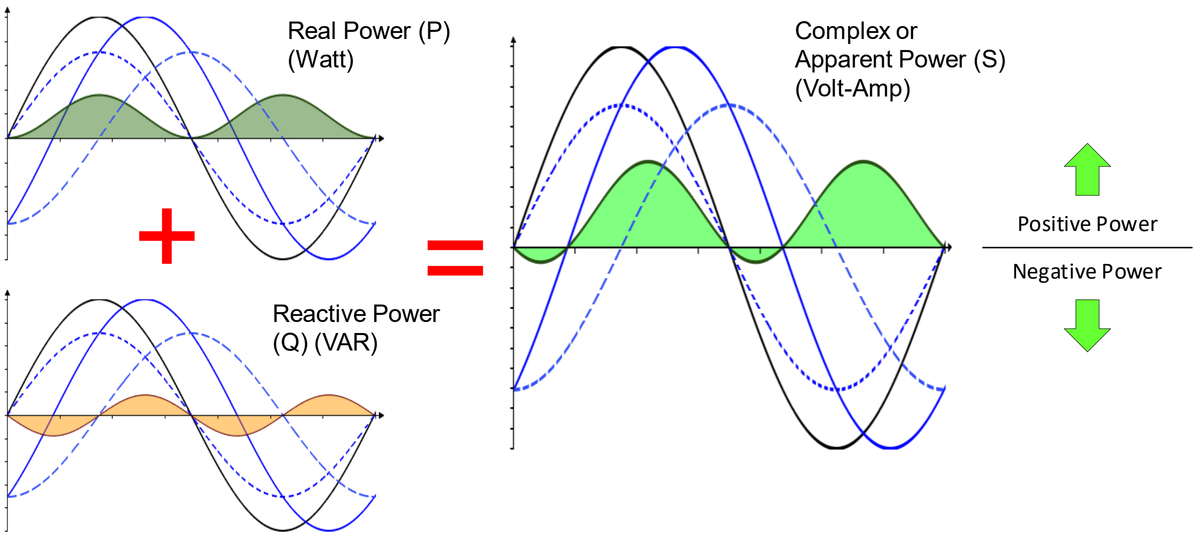
Harmonic current and excess heating:
Displacement Power factor review



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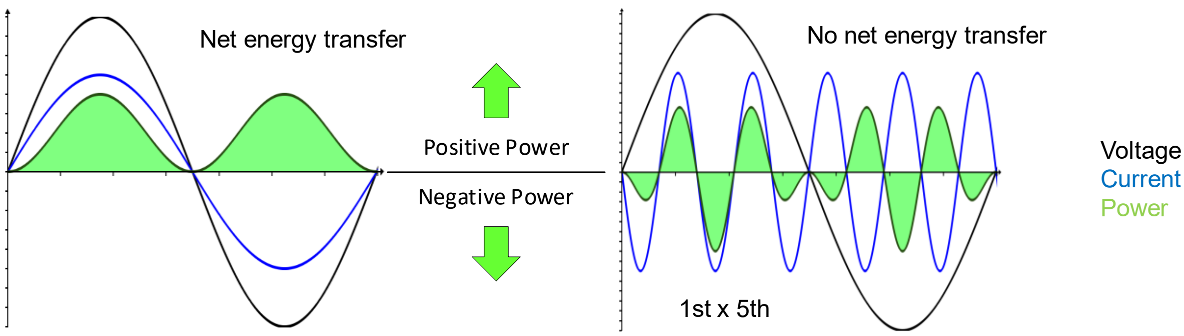
Harmonic current and excess heating:
Frequency and power flow



For "real" net electric energy transfer (watt-hours), the voltage and current must be at the **same** frequency and at least partly in-phase. (V and I phasors must not be perpendicular.)

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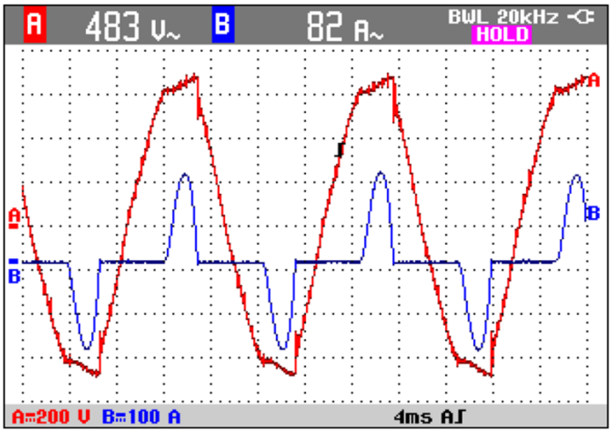
Harmonic current and “flat-topping”:
Reduced voltage sag “ride through”



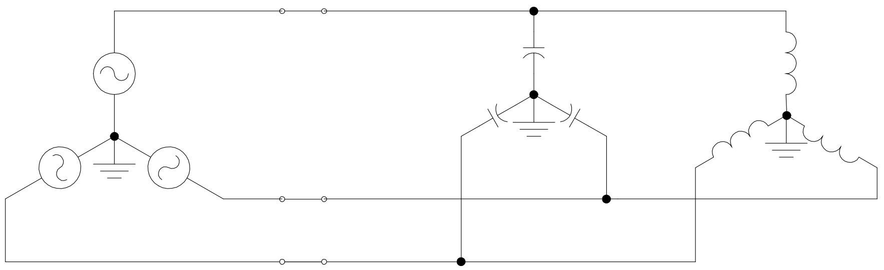
- Note the “flat” top of the voltage waveform caused by the current shown.
- The “flat-topping” reduces the peak DC voltage in this and other rectifiers, reducing the energy stored and thereby reducing their voltage sag ride-through capability.

Harmonic phase sequence

- Remember - unbalanced 60Hz voltages can be broken down into positive, negative, and zero-sequence components
- Harmonic voltages and currents, even if perfectly “balanced,” are also classified as either positive, negative, or zero sequence
- Negative sequence and zero sequence harmonics have unique impacts.

Harmonic phase sequence

- Harmonic phase sequence becomes important for motors and on grounded-wye systems



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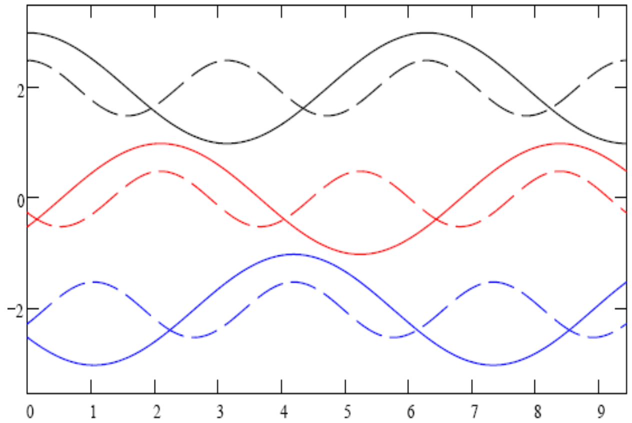
Negative sequence harmonics

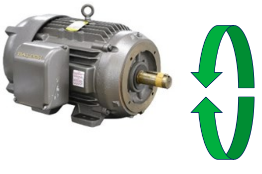
A graphical example

Three-phase fundamental and 2nd harmonic waveforms



Sequence is ABC (positive) for fundamental, ACB (negative) for 2nd harmonic.

Negative sequence voltage harmonics create opposing torque in motors; increasing motor heating and reducing efficiency.



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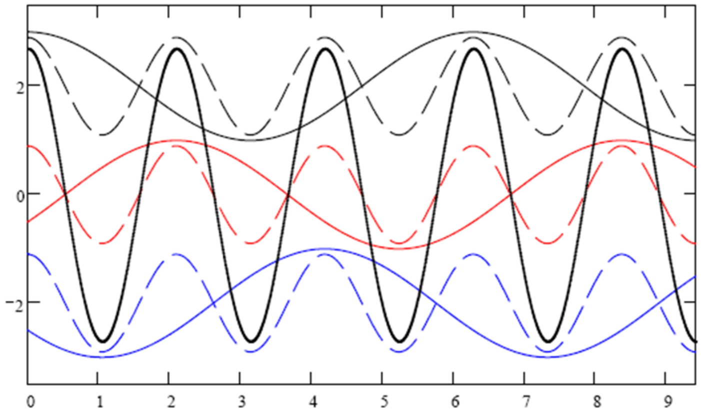
Zero sequence harmonics in three-phase systems

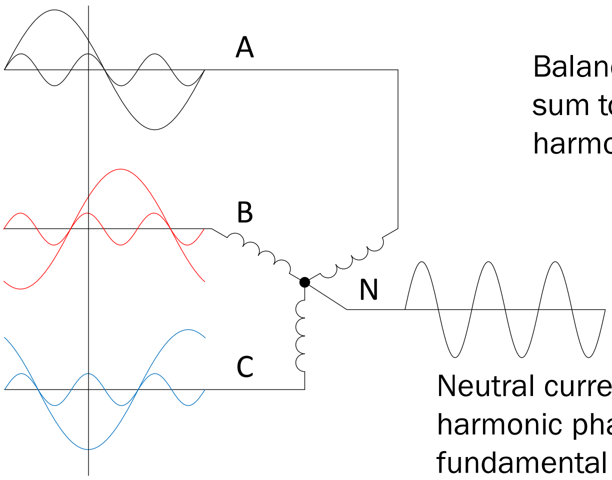
"Triplen" harmonics: odd multiples of the third harmonic

Three-phase fundamental and 3rd harmonic waveforms



Third harmonic current waveforms are in phase on all three phases – zero sequence – they will add in the neutral

Triplen Harmonics:
Odd multiples of the third harmonic



Balanced fundamental currents sum to zero, balanced third harmonic currents are in-phase

Neutral current = 300% of third harmonic phase current but has no fundamental current

Triplen harmonics:

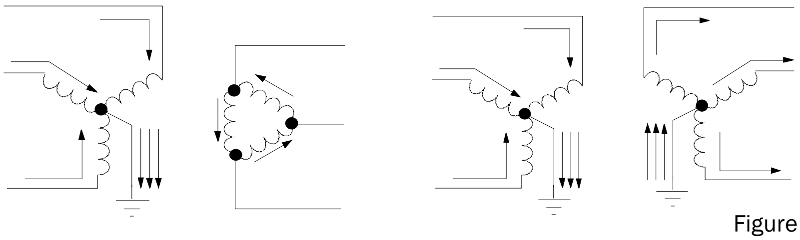


Figure from [1]

- Balanced triplen harmonic currents are blocked by delta transformer windings, but produce heat in those windings
- Unbalanced harmonic currents and voltages may not produce the same effects as their balanced counterparts.
  - Unbalanced harmonic voltages and currents can be broken down into a set of positive, negative, and zero sequence harmonic symmetrical components – more complex analysis

Positive, negative, and zero sequence harmonics

Positive	Negative	Zero
1	2	3
4	5	6
7	8	9
10	11	12
13	14	15
16	17	18

Harmonics analysis in power systems - overview

- Analysis range – usually up to 50^{th}
  - It can be helpful to look for higher harmonics
- Most non-linear elements in the system are end-user loads - power electronics
  - IBR – Inverter Based Resources may also be an issue
- When referring to “harmonics” we may need to specify current, voltage, or power
- Harmonic analysis is location-specific because resulting voltage distortion depends on system impedance

Power system quantities with harmonics

- Apparent power (S): Volt-Amps, VA

$$S = V_{rms} \cdot I_{rms}$$

  - Not harmonic-specific or dependent
    - Could have voltage and current waveforms made up of different harmonics

$$V_{rms} = \sqrt{\sum_{h=1}^{h_{max}} {V_h}^2}$$

V_h is the RMS value of the individual harmonic voltages.

FPQ includes several apparent power and distortion power values; see pgs. 208-212.

Power system quantities with harmonics

- Active power (P) – Watts, W

$$P = \frac{1}{T}\cdot\int_0^T v(t)\cdot i(t)\,dt \qquad P = \sum_h \left(V_{h\_rms}\cdot I_{h\_rms}\cdot\cos\theta_h\right)$$

  - Harmonic specific – only current in phase with, **and** at the same frequency as the voltage can deliver useful work: REAL power
  - Other combinations (different frequencies or voltage and current phasors that are perpendicular create reactive or distortion power
    - However, ALL current contributes to system losses though: I^2R
  - Some instruments or software distinguish fundamental frequency power from harmonic contributions
  - It is usually accurate enough to only use fundamental values when calculating active power (P)
  - ***Download and experiment with PF Teaching Tool and Power Quality Teaching Toy via class website.***

Power Factor

Displacement power factor -Due to phase shift between V and I at fundamental frequency

$$DPF = \cos\theta$$

True Power Factor – includes harmonics

$$PF = \frac{P}{S} = \frac{Active\_power}{Apparent\_power}$$

True Power Factor may also be called “Power Factor” or “Total Power Factor”

Total harmonic distortion

- THD – common measure of harmonic distortion

$$THD = \frac{\sqrt{\sum_{h=2}^{h_{max}} M_h^2}}{M_1} = \frac{\sqrt{M_2^2 + M_3^2 + .. + M_{hmax}^2}}{M_1}$$

M_x = RMS voltage or current at a given harmonic number "x"

Distortion Power Factor

- Relates RMS value of the distorted current, including the fundamental current, to RMS value of the fundamental current only (not in texts)

$$\frac{I_1}{I_{RMS}} = PF_{dist} \qquad I_{RMS} = \sqrt{\sum_{h=1}^{h_{max}} I_h^2} = I_1 \cdot \sqrt{1 + THD_I^2}$$

$$PF_{dist} = \frac{1}{\sqrt{1 + THD_I^2}}$$

The impact of harmonic current on true power factor

- Typical power systems:
  - $P_1 \approx P_{total}$: nearly all real power flow is at the fundamental frequency
  - Voltage distortion is low
- Using these generalities, we can say:

$$PF_{true} = \frac{P_1}{V_{1rms} \cdot I_{1rms}} \cdot \frac{1}{\sqrt{1+THD_I^{\,2}}} = PF_{disp} \cdot PF_{dist}$$

Therefore, current distortion results in a lower true power factor

Total demand distortion

- TDD – addresses the fact that very small and very distorted currents are not normally a problem
- TDD provides a fixed threshold when used in limits because I_L is a fixed value for a given facility

$$\mathrm{TDD} = \frac{\sqrt{\sum_{h=2}^{h_{max}} I_h^{\,2}}}{I_L}$$

I_L = peak demand load current (RMS) at fundamental frequency

Coming up...

- More power system quantities with harmonics
- Locating harmonic sources
- System response
- Transformer derating
- Interharmonics
- Mitigation