Today: Harmonic fundamentals
FPQ chapters 6 and 7, PSQ chapters 5 and 6

- A suggestion on Homework 2 problem 3
- Voltage and Current Harmonic Distortion
- Power system quantities with harmonics
- Harmonic Indices
- Harmonic phase sequence
- Triplen harmonics
- Harmonic sources

References:
http://users.ece.utexas.edu/~grady/POWERFAC.pdf
Homework 2 problem 3 suggestion

When finding I_{start} to limit the voltage drop at bus “A”, work in per-unit with a single common MVAbase. For example:

- Motor’s nominal voltage is 460V Line-to-line
- Short circuit MVA of the primary system at bus “A” is 30MVA
- Transformer is 1MVA with 4% impedance

Solution: We’ll use the transformer MVA as the common MVAbase.

\[ MVA_s = 30 \text{ MVA}, \quad MVA_T = 1 \text{ MVA} \]

\[ X_{s\_pu1} = \frac{1 \cdot \text{pu} \cdot \frac{MVA_T}{MVA_s}}{0.033 \text{ pu}} \quad \text{Convert system impedance to common MVAbase} \]

\[ I_{pu_{460}} = \frac{MVA_T}{\sqrt{3} \cdot 460 \text{ V}} = (1.255 \cdot 10^3) \text{ A} \quad \text{Find per-unit current at 460V} \]

\[ I_{max} = \frac{1 - 0.95}{X_{s\_pu1}} \cdot I_{pu_{460}} = (1.883 \cdot 10^3) \text{ A} \quad \text{Find I_{max} with Ohm's Law} \]

Text updates and announcements

  - Get a copy of this standard from the IEEEXplore site via the UI library web site.
Harmonics – quick review

- Any repetitive waveform can be expressed as a sum of sine waves at frequencies that are integer multiples (HARMONICS) of the fundamental frequency of the waveform.
- This allows us to use superposition in analysis

General Principles

- Harmonic problems are often continuous in nature
  - Heating
  - Interference
- Some harmonic distortion in the supply voltage may be found almost everywhere
- Actual problems due to harmonics are not as common as problems due to voltage sags
- Percentage of nonlinear load continues to grow
Harmonic distortion

Cause: “non-linear” loads
Current is not a linear function of the applied voltage at a given frequency, and is therefore distorted

Result:
- Distorted current passing through frequency-dependent system impedances → distorted voltage
- Distorted voltage supplied to linear loads → distorted currents in other parts of the electrical system
- If load is frequency-dependent (inductive, capacitive, both) current distortion may be higher than voltage distortion even for linear loads

Harmonics in power systems - overview

- Analysis range – usually up to 25th or 50th
  - It can be helpful to look for higher harmonics
- Most non-linear elements in the system are end-user loads - power electronics
- When referring to “harmonics” we may need to specify current or voltage
- Because resulting voltage distortion depends on system impedance, harmonic analysis is location-specific
Power system quantities with harmonics

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

\[ S = V_{\text{rms}} \cdot I_{\text{rms}} \]

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

\[ V_{\text{rms}} = \sqrt{\sum_{h=1}^{h_{\text{max}}} \left( \frac{1}{\sqrt{2}} \cdot V_h \right)^2} \]

where \( V_h \) is the peak magnitude 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

\[ P = \frac{1}{T} \int_{0}^{T} v(t) \cdot i(t) \, dt \]
\[ P = \sum_{h} \left( V_{h_{\text{rms}}} \cdot I_{h_{\text{rms}}} \cdot \cos \theta_h \right) \]

- Harmonic specific – only current in phase with, and at the same frequency as the voltage can deliver useful work: REAL power
- All other combinations (different frequencies and/or phase shift) create apparent or distortion power only
  - 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

\[
PF = \frac{P}{S} = \frac{\text{Active\_power}}{\text{Apparent\_power}}
\]

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

Total harmonic distortion

- THD – common measure of harmonic distortion

\[
THD = \sqrt{\sum_{h=2}^{h_{\text{max}}} \frac{M_h^2}{M_1}} = \sqrt{\frac{M_2^2 + M_3^2 + \ldots + M_{h_{\text{max}}}^2}{M_1^2}}
\]

\( M_x = \text{RMS voltage or current at a given harmonic number “}x\text{”} \)
Distortion Power Factor

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

\[
\frac{I_1}{I_{RMS}} = PF_{\text{dist}}
\]

\[
I_{RMS} = \sqrt{\sum_{h=1}^{h_{\text{max}}} I_h^2} = I_1 \sqrt{1 + \text{THD}_1^2}
\]

\[
PF_{\text{dist}} = \frac{1}{\sqrt{1 + \text{THD}_1^2}}
\]

The impact of harmonic current on true power factor

- Typical power systems:
  - \(P_1 \approx P_{\text{total}}\): nearly all real power flow is at the fundamental frequency
  - Voltage distortion is low

- Using these generalities, we can say:

\[
PF_{\text{true}} = \frac{P_1}{V_{\text{rms}} \cdot I_{\text{rms}}} \cdot \frac{1}{\sqrt{1 + \text{THD}_1^2}} = PF_{\text{disp}} \cdot PF_{\text{dist}}
\]

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

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

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

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
Harmonic phase sequence

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

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Harmonic phase sequence

- A graphical example of harmonic phase sequence
  - Three-phase fundamental and 2\textsuperscript{nd} harmonic waveforms

  ![Graph of harmonic phase sequence](image)

  Sequence is ABC for fundamental, ACB for 2nd harmonic

Triplen harmonics on three-phase systems

- Triplen harmonics in a three-phase system
  - Three-phase fundamental and 3rd harmonic waveforms

  ![Graph of triplen harmonics](image)

  Third harmonic waveforms are in phase – they 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

- Balanced triplen harmonic currents are blocked by delta
  transformer 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
Harmonic sources: Commercial loads

- Single-phase power supplies
  - Older power supplies stepped down AC supply first with a transformer, then rectified it
    - What are the advantages and disadvantages of this approach?
  - Now most electronic devices use switched mode power supplies.
    - Advantages and disadvantages?

Switch-mode power supplies

![Switch-mode power supply diagram]

Current on the AC Line side
Switch-mode power supply harmonic spectrum

Other commercial-load issues: magnetic and electronic ballasts

All figures from [1]
Other commercial-load issues:

- Efficiency is driving the use of ASDs in HVAC systems
- Harmonic issues need to be considered in building electrical systems
  - Could be a significant problem when older buildings become home to computers and modern lighting systems

Industrial loads

- Three-phase power converters
  - Variable speed drives, AC or DC, employing six-pulse rectifiers are generally the most common source of harmonics in industrial facilities
  - Triplen harmonics not a problem – three-phase drives don’t produce them
  - PWM ASD is the most popular (Pulse-Width-Modulation)
Harmonic sources – Variable speed drive

Event Details/Waveforms

Harmonic sources – variable speed drive

Waveform harmonics
Some PWM drive waveforms

Supply Voltage and current

Output Voltage and current

Numerous frequencies present:
- 60Hz
- Lower harmonics
- Switching frequencies
- Harmonics in the voltage pulses

Coming up...

- More power system quantities with harmonics
- Locating harmonic sources
- System response
- Effects of harmonic distortion
- Interharmonics