University of Idaho
College of Engineering

ECE 528 – Understanding Power Quality

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

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Lecture 10

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Today…

- Harmonic analysis PSQ Ch. 5 & 6, FPQ Ch. 6 & 7
  - Locating Sources
  - System response
  - Parallel and series resonance
  - Harmonic distortion evaluations
  - Principles of harmonic control
    - Utility control
    - End-user control
  - Example IEEE-519 evaluation

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Harmonic distortion evaluations (PSQ section 6.4)

- Why?
  - Solve or prevent problems
    - Voltage distortion
    - Damaged equipment
  - Evaluate changes
    - New capacitors
    - New non-linear loads
  - Study solution alternatives
    - Filters
    - Relocating capacitors

Why evaluate harmonics – some examples

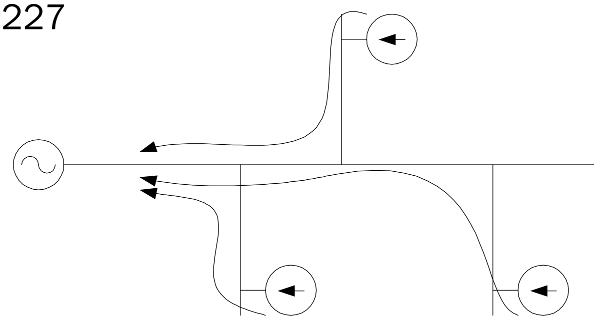
- Why do fuses on a capacitor bank keep blowing?
- The gas company is reporting 180Hz AC voltage on their pipeline.
- Can we add an 1800kVAR capacitor bank near this industrial customer?
- A customer wants to install a 300Hp motor with a variable speed drive.
- Does a facility meet the IEEE-519 current distortion limits?

Utility system harmonic evaluations
Voltage distortion

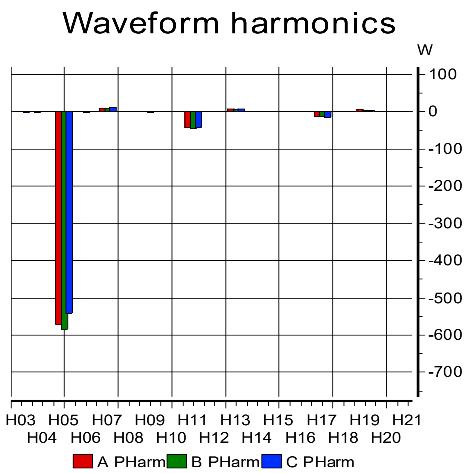
- If the utility system impedance does not contain resonances near common harmonic frequencies, and end-user loads do not inject excessive harmonic current into the system, voltage distortion problems are unlikely.
- Utility engineers include system frequency response in design decisions
  - Avoid resonances near common harmonic frequencies
  - Primarily affects capacitor size and location

Locating harmonic sources

- Method described in the text:
  - Follow the current "downstream" to the load
  - See PSQ p. 227



Another way to find harmonic sources

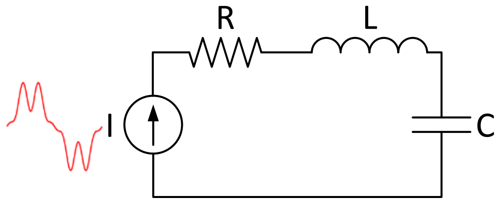


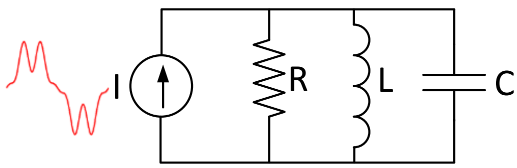
By convention, positive power flows from the source to the load. Non-linear loads (harmonic sources) deliver power at harmonic frequencies back toward the source.

System response to harmonics

- The most significant issue is that one of the resonant frequencies of the system will coincide with a common harmonic frequency
- Utility system capacitors generally create parallel resonances with the system's impedance

Parallel and series resonance (FPQ pgs 231-240)

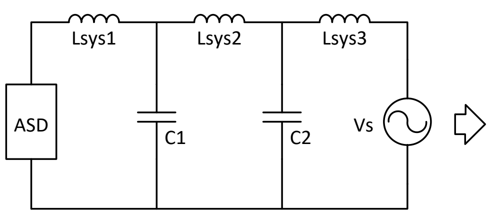




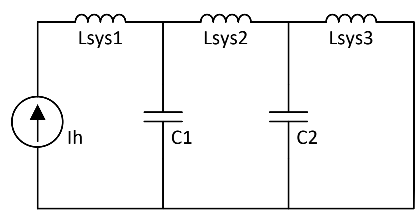
- Series resonance:
  - Low impedance near resonant frequency
  - $Z_C + Z_L \rightarrow 0\Omega$
  - High current through Z_C (capacitor) and Z_L (transformer)
- Parallel resonance:
  - High impedance near resonant frequency
  - $Z_C \,||\, Z_L \rightarrow \infty\ \Omega$
  - High voltage across $Z_C \,||\, Z_L$

Parallel resonance (FPQ pgs 246-249)

- There can be multiple resonant frequencies:



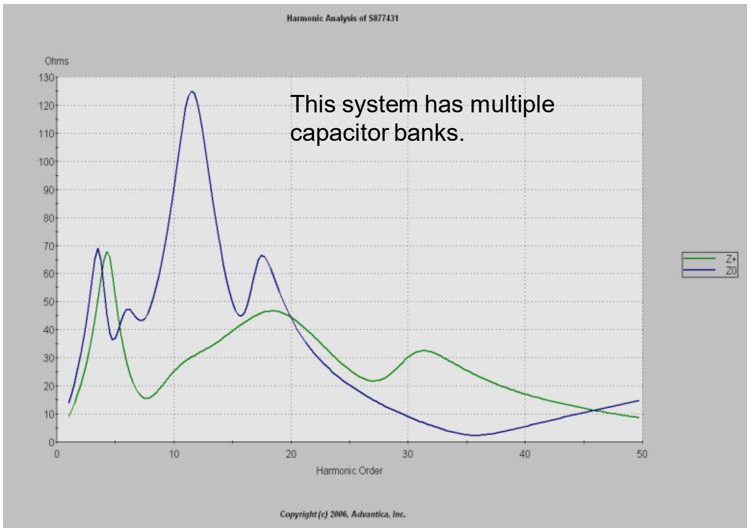
Basic system with two capacitors and an ASD



Thevenin Equivalent for analyzing contribution of ASD

$$\frac{1}{2\cdot\pi\cdot\sqrt{L_{sys1}\cdot C_1}} \neq \frac{1}{2\cdot\pi\cdot\sqrt{\left(L_{sys1}+L_{sys2}\right)\cdot C2}}$$

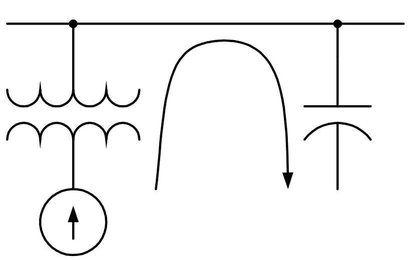
Computer modeling – frequency scan



- The size and location of capacitor banks affects the system's frequency response.
- This plot is impedance versus harmonic order, so peaks correspond to parallel resonances and valleys correspond to series resonances.
- Positive (or negative) sequence harmonics have different current paths than zero-sequenced harmonics, hence different system frequency response.

Series resonance (FPQ pgs 250-251)

- Created by series combination of transformer and capacitor
- May affect customers with no non-linear load
- May damage utility capacitors near customers with non-linear loads



Utility system harmonic evaluations
Limiting Voltage distortion

- IEEE 519 table 1 (PSQ table 6.1, FPQ table 7.1 based on IEEE-519-1992 are similar)
  - Two factors drive voltage distortion
    - Harmonic current injection from non-linear loads
    - System response to harmonic frequencies

$$THD = \frac{\sqrt{\sum_{2} V_h^2}}{V_1}$$

Standard definition

$$THD = \frac{\sqrt{\sum_{2} V_h^2}}{V_{nominal}}$$

IEEE-519 definition used for voltage distortion limits

Using nominal voltage in IEEE-519 Vthd prevents normal voltage fluctuations from changing the calculated THD for a given level of harmonic content.

Utility harmonic evaluations
Limiting harmonic current injection

- Process for existing loads
  - Isc (available short-circuit current) from system simulations
  - Peak demand from billing data
    - Determine limits on TDD and individual harmonics
  - Monitor for 1-week (ideally near normal peak)
  - Statistical analysis:
    - Daily 99th percentile limits: 2 times limits in table (3s average)
    - Weekly 99th percentile limits: 1.5 times limits in table (10-minute averages)
    - Weekly 95th percentile limits: limits in table (10-minute averages)
  - Report results to customers
  - Discuss mitigation plan if necessary

Utility harmonic evaluations
Limiting harmonic current injection

- Process for proposed loads
  - Isc from system simulations
  - Peak demand from calculations
  - Provide information to customer
    - System impedance information
    - Requirements/limits
  - Customer education
  - Follow-up: check load when installed

Harmonic evaluations in end-user facilities

- Highest distortion levels are in end-user facilities
- IEEE 519-2022 applies distortion limits at the PCC - distortion may be higher downstream
- Meeting IEEE 519-2022 may be more challenging for isolated non-linear loads
  - Linear loads can help dilute the harmonic content of the load current

End-user harmonic evaluations

- Generally in response to a harmonic problem
  - Failed capacitors
  - Interference
  - Failure to meet IEEE-519 at PCC
- May be conducted by utility
  - Identify sources
  - Recommend mitigation

Principles of harmonic control

- Determine a “problem” level – usually IEEE 519 thresholds
- Causes
  - High harmonic currents
  - Path impedance
    - Distorted current through system impedance creates voltage distortion
    - System response may magnify impact of certain harmonics (resonances or near-resonances)

Principles of harmonic control - Solutions

- Reduce harmonic currents
  - Use variable frequency drives for variable load only
  - Add inductance
  - Convert to 12-pulse with transformers
  - Use “low-distortion” variable frequency drives (active rectifier)
  - Specify IEEE 519 compliance in requirements
- Filter
  - Shunt – provide low-impedance path away from rest of system
  - Series – increase impedance to harmonic currents near load
  - Active – Provide harmonic currents from another source

Principles of harmonic control

- Solutions continued…
  - Modify system response
    - Remove a capacitor
    - Move a capacitor
    - Change a capacitor’s size
    - Add a reactor
    - Add a shunt filter

Modeling harmonic sources

- Computer simulation:
  - Harmonic studies, load flow, fault studies
- Impacts of simulation characteristics
  - Harmonic loads modeled as fixed-spectrum current sources
    - Voltage distortion is affected by current distortion.
    - Current distortion is affected by voltage distortion.
      - Is the assumption that the harmonic spectrum is fixed a conservative assumption?

Modeling harmonic sources

- Sources of harmonic current data for the load
  - Measure the current directly
    - Existing loads
  - Use manufacturer's data
    - Proposed loads
  - Make assumptions about load characteristics
    - Table 6.3 from PSQ – characteristic harmonic magnitudes for different loads

A real-world example (slide 1)

- Question:
  - Does the customer's load current meet IEEE-519?
- Data needed:
  - PCC – point of common coupling – where the standard applies
  - Demand current
  - Short-circuit current
  - Voltage
  - Harmonic spectrum of the load current

Example: IEEE-519 evaluation (slide 2)

- Customer is primary-metered at 12.47kV$_{L\text{-}L}$ (3-phase AC RMS)
  - PCC is at primary meter on high voltage side of the transformers at the facility
- From revenue metering, or recording
  - Demand current I_L, is: 244A
- From computer fault analysis
  - Short circuit current, I_{SC}, is: 3,555 A
  - Which row of IEEE-519, table 2 applies?

    (Table 7.2, pg 241 of FPQ is the same.)

$$\frac{I_{sc}}{I_L} = \frac{3555A}{244A} = 14.6$$

Example: IEEE-519 evaluation (slide 3)
IEEE 519 current distortion limits (from 2022 edition, Table 2)

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order[b]						
I_{SC}/I_L	$2 \le h < 11$[a]	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a] For $h \le 6$, even harmonics are limited to 50% of the harmonic limits shown in the table.

[b] Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c] Power generation facilities are limited to these values of current distortion, regardless of actual I_{sc}/I_L unless covered by other standards with applicable scope.
where:
I_{sc} = maximum short-circuit current at PCC
I_L = maximum demand load current at PCC under normal load operating conditions

This table is for 120V through 69kV.

The footnotes are important.

Example: IEEE-519 evaluation (slide 4)
Analyzing the recorded harmonic data

- The power quality recorder can only measure actual current and voltage
  - We need to calculate values involving I_L (the normal peak or "demand" current)
  - Spreadsheet – Calculate:

$$\%I_L = \frac{I_h}{I_L} \cdot 100\%$$

$$TDD = \frac{\sqrt{\sum_2 I_h^2}}{I_L} \cdot 100\%$$

Example: IEEE-519 evaluation (slide 5)
Harmonic testing during non-peak conditions

- Use current harmonic limits in **Amps** based on I_L : the maximum normal (fundamental) load current

Measured harmonic amps < limits

- More linear load won't change that
- Adjust for missing non-linear load if necessary
  - Compare amount of missing non-linear load to test results
  - May use multiplier on recorded harmonic current to account for missing load

Measured harmonic amps > limits

- More load won't change the result, regardless of the nature of that additional load.

We can add in missing linear and/or non-linear load "on paper" to evaluate the system.

Example: IEEE-519 evaluation (slide 6)
Analyzing the data – 1-week 95th percentile values

h	Amps	%	h_pu^2
1	244	100	1
3	3.172	1.3	0.000169
5	22.936	9.4	0.008836
7	7.808	3.2	0.001024
9	1.22	0.5	0.000025
11	5.124	2.1	0.000441
13	4.148	1.7	0.000289
15	0.732	0.3	0.000009
17	0.732	0.3	0.000009
19	0.488	0.2	0.000004
21	0.488	0.2	0.000004
23	0.244	0.1	0.000001
25	0.244	0.1	0.000001

A spreadsheet may be easiest…

$$TDD = \frac{\sqrt{\sum_2 {I_h}^2}}{I_L} \cdot 100\%$$

$$\sum_2 I_h^2 = 0.010812$$

$$TDD = 10.4\%$$

Example: IEEE-519 evaluation (slide 7)
Conclusions of this analysis

- This customer exceeds the IEEE 519 current harmonic distortion limits for the 5th, and 11th harmonics, and for the TDD.
- Now we have to tell the customer
  - Explain your analysis
  - Help them reach the same conclusion
  - Explain their options and why action is important

Utility system harmonic control

- Emphasis is on recognizing and avoiding potential problems
  - Frequency response should be checked at every capacitor bank
  - Spot measurements should be used to check/verify computer simulations
  - Harmonic distortion can be included in other power quality recordings
  - It’s possible to turn power factor correction capacitors into shunt filters

End-user harmonic control

- General steps to minimize problems
  - Know your sources
  - Include filters near the sources
  - Put PF correction capacitors near the loads that need them
  - Check wiring
    - Adequate size given true RMS current?
    - Could triplen harmonics in the neutral be an issue?

Next time…

- Homework 3 discussion
- More harmonic analysis
  - Transformer derating
- Harmonic control devices
- Filters
- Interharmonics