ECE 528 – Understanding Power Quality

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

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Lecture 12

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Today…

- Motor bearing currents
- More on Interharmonics and supraharmonics
- Harmonic control devices
  - In-line reactors (chokes)
  - Zigzag transformers
  - Passive filters
  - Active filters
  - Designing a harmonic filter
- Harmonic standards

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Motor bearing currents

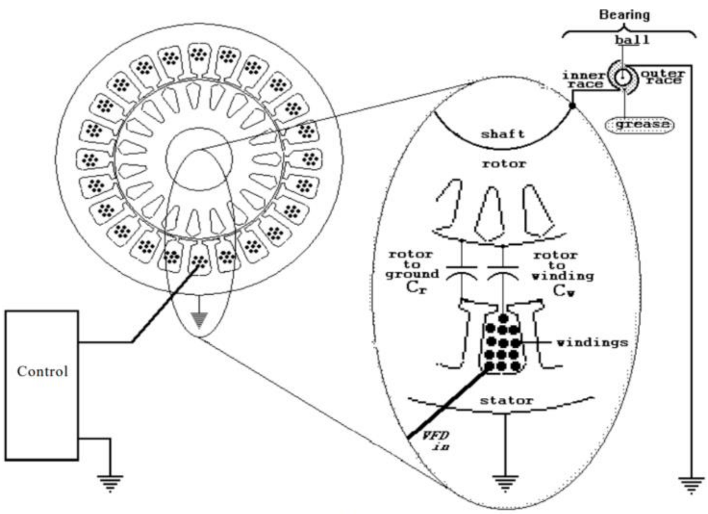


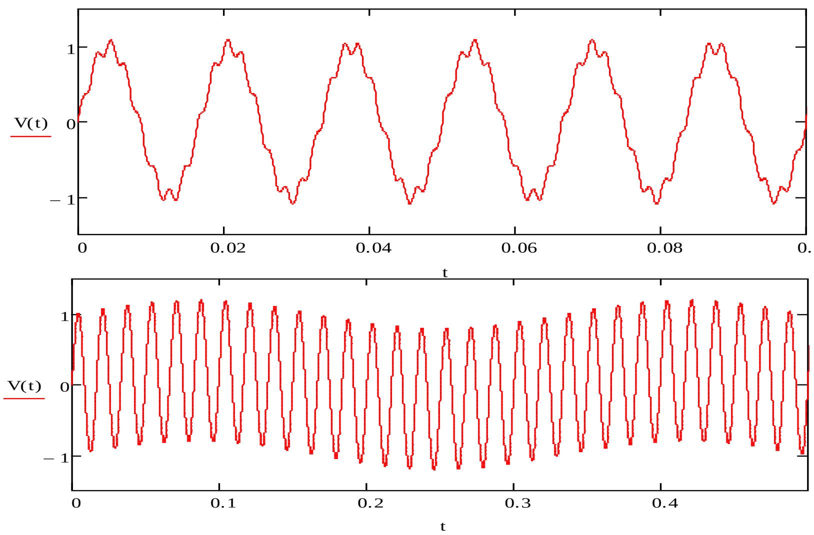
*Figure from NEMA Application Guide for AC Adjustable Speed Drive Systems

- One cause: "common mode" (zero sequence) voltage
  - Conventional voltage unbalance
  - Zero sequence harmonics
- Uses capacitive coupling between stator and rotor
  - Proportional to voltage magnitude and frequency

Interharmonics: Definitions (PSQ pg. 250)

- Harmonic: Integer multiple of the fundamental frequency
- Interharmonic: Non-integer multiple of the fundamental frequency
  - Sub-harmonic: frequency less than the fundamental frequency
  - Supraharmonic: frequencies in the 2kHz to 150kHz range

Interharmonics examples:



60Hz + 500Hz
Repeats every 3 cycles

60Hz + 3Hz
Repeats every 20 cycles

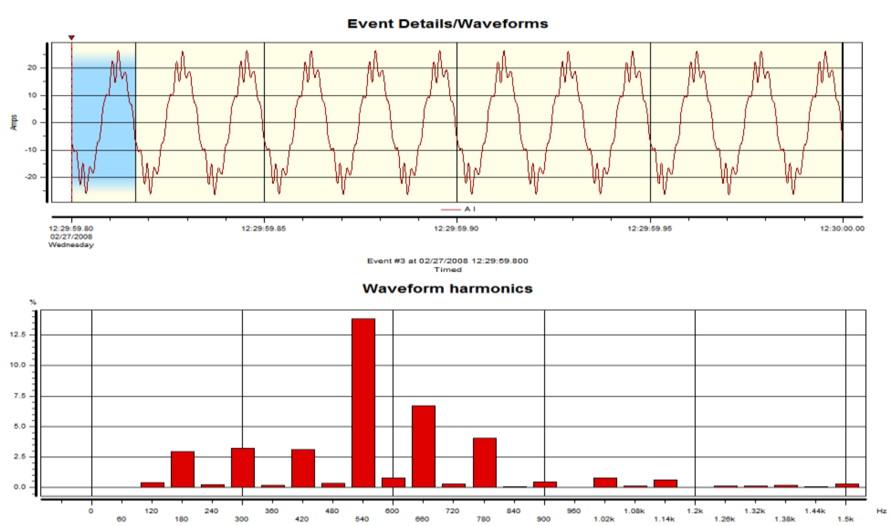
Interharmonic and Supraharmonic sources

- Power-line-carrier signals
- Frequency converters
  - Variable Frequency Drives
  - Cycloconverters (solid-state direct frequency converter)
  - Induction furnaces
- Modern inverters - solar systems
- Arcing loads
- Load variations

Interharmonics issues

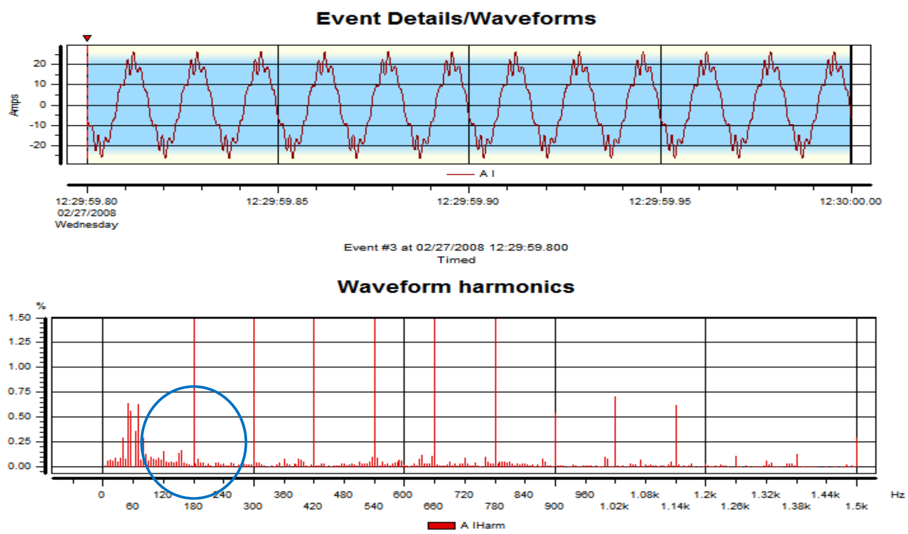
- Analysis
  - Power quality instruments may not accurately measure them
- Impacts
  - Heating and reduced equipment life – like regular harmonics
    - Low frequency (<2 x fundamental frequency) is associated with the most significant impacts
      - Hard to filter – can cause mechanical vibration and additional resonances
    - Effect at higher frequencies is less distinguishable from conventional higher frequency harmonics.
  - Oscillations in mechanical systems
  - Interference with power-line-carrier systems
  - Tuned filters may not work because of the variability of the harmonic spectrum

Interharmonics – data analysis issue, 1-60Hz cycle



Spectrum using one 60Hz cycle

Interharmonics – data analysis issue



Spectrum using 12-cycles at the fundamental frequency in the harmonic analysis.

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Principles of harmonic control

- Solutions
  - Eliminate or reduce harmonic currents
    - Only use VFDs where they're needed.
    - Use VFDs alongside line-connected motors; i.e. 50hp line-connected with 50hp VFD for 0-100hp range.
    - Dilute the harmonic content of the current with linear load where practical – helps with meeting IEEE-519
    - Convert to 12-pulse or 18-pulse VFDs (use transformers to phase-shift)
    - Use "low-distortion" VFDs
    - Specify IEEE 519 compliance in bid requests

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Principles of harmonic control continued…

- Solutions
  - Filter as close to the harmonic source as practical
    - Reduces losses and voltage distortion in the facility
    - Protects the most other equipment from impacts
  - Filter types
    - Series – increase impedance to harmonic currents near load
    - Shunt – provide low-impedance path away from rest of system
    - Active – Provide harmonic currents from another source

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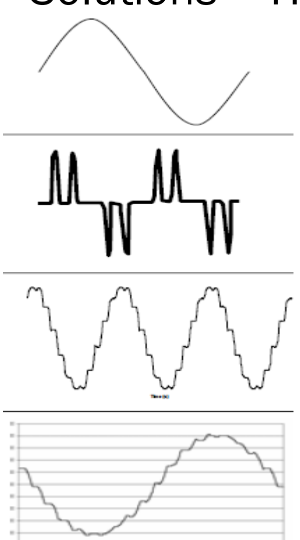
Solutions – Higher Pulse Rectifier



- Linear load (i.e. motors) no rectifier
- Six-Pulse Rectifier
- Twelve-Pulse Rectifier
  - Formed by connecting two six pulse rectifiers in parallel with a 30° phase shift – delta-wye transformer. THDi: ~10%
- Eighteen-Pulse Rectifier
  - Formed by connecting (3) six pulse rectifiers in parallel with a 20° phase shift THDi: ~5%

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Solutions – "Low distortion"/Active front end VFDs

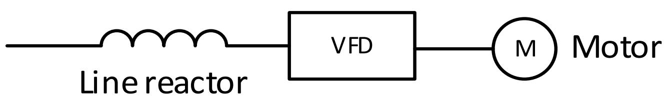
- Active IGBT Bridge instead of passive diodes
  - Actively modulated to control harmonic current
- Advantages
  - Supply current has very little harmonic content; THDi ~2-3%
  - Has ability to boost voltage should supply drop
  - Eliminates need for a separate harmonic filter
  - Eliminates harmonic current at the source – benefits neighboring equipment
- Disadvantages
  - Higher cost when compared to diode rectifier
  - Larger footprint

Harmonic mitigation: Passive filters

- Capacitors and inductors can be arranged to produce high or low impedances at certain frequencies (See HW1)
- Resistors can be added to provide damping
- Shunt passive filters – provide a low-impedance alternate path
- Series passive filters – increase the series impedance for certain frequencies

Harmonic mitigation: In-line reactors (chokes)

- Simply a series inductance
- Presents a series impedance that is directly proportional to frequency
- Forces DC bus capacitor to charge more slowly – smooths out the current waveform
- Typically reduces THD to 25-35%
- May not reduce harmonic levels to below IEEE 519 limits
- Must carry full load current
- Additional benefit: Very effective at protecting drive against damage or nuisance tripping due to voltage transients from events like capacitor switching



In-line reactors (chokes)

- Sizing the in-line reactor
  - Line reactors are typically described as “a 3% reactor”, 3% to 5% are common
  - Size is based on the VA base of the drive
  - Using 750VA/hp for VA base is typical

$$X_{L\_5\%} := 0.05 \frac{(V_{base})^2}{VA_{base}} \qquad L = \frac{X_L}{2\pi \cdot f}$$

  - Inductance in Henrys is based on X_L at the <u>fundamental</u> frequency

Line Reactor example:

- What is the size, in millihenries, of a 5% line-reactor for a 50Hp, 480V Variable Frequency Drive?

$$M_{hp} := 50\ \mathbf{hp} \qquad Drive_{kVA} := M_{hp} \cdot \frac{0.75\ \mathbf{kVA}}{\mathbf{hp}} = 37.5\ \mathbf{kVA}$$

$$Z_{drive} := \frac{(480\ \mathbf{V})^2}{Drive_{kVA}} = 6.144\ \mathbf{\Omega} \qquad L_{5\%} := \frac{0.05 \cdot Z_{drive}}{2\ \pi \cdot 60\ \mathbf{Hz}} = 0.815\ \mathbf{mH}$$

Note: Commercial reactor sizes may be based on 1kVA/hp and nominal utilization voltage; 460V in this case.

Sidebar – Mathcad Prime trick: using special characters in names and literal subscripts

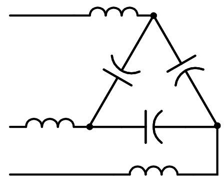
- Prime won't let you use certain characters in names or in literal subscripts, but sometimes those characters would be helpful.
- You can define values using a text string that you then paste into a math region to use characters like % in names and subscripts.
  - Example: Type (@ID L (@SUB 5%)) into a text box. Edit this string as needed. You may need quotes as in (@ID M (@SUB "a:b"))
  - Copy the text from the text box and paste into an empty math region.

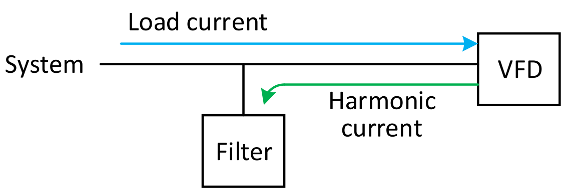
Text box: (@ID L (@SUB 5%))

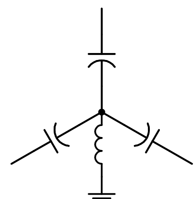
Math region: $L_{5\%} :=$

Harmonic mitigation: Shunt Passive filters

- Provides a low-impedance alternate path for harmonic current
- Less expensive than active filters
  - Designed specifically for harmonic filtering
  - Typically reduces THD to 5-12%
  - May also provide displacement Power Factor correction
- Filter design procedure - See FPQ section 7.4.3, p259 for a filter design case study







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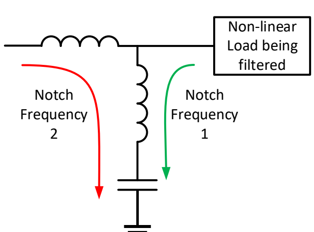
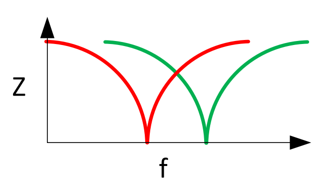
Filtering the load versus the source

- A shunt passive filter alone will filter harmonic current from all sources, possibly overloading the filter.
- With a combination of shunt and series elements, the L-C series impedance is different depending on the source of the current.





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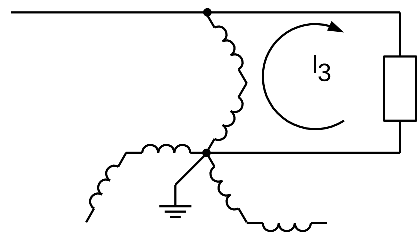
Harmonic mitigation: Zigzag transformers

- Used for zero-sequence currents
- Commercial facilities – single-phase non-linear loads
- Provides a path for zero-sequence currents between phase and neutral conductors
- Useful in existing facilities



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Harmonic mitigation: Active filters

- Use power-electronics to inject cancelling current in the non-linear load's current waveform – can inject multiple frequencies simultaneously
- Results in minimal distortion on the source side
- No resonance concerns
- No overloading concerns
- May also correct power factor and flicker
- More expensive
- Analogous to noise-cancelling headphones

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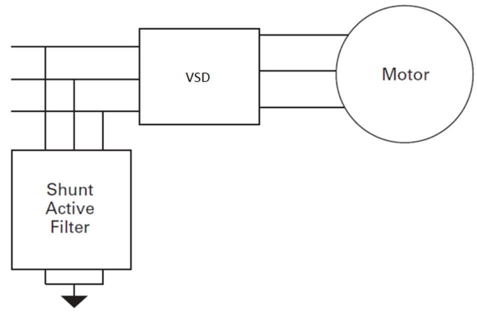
Harmonic mitigation: Active Filters

- Expensive
- Very effective
- Applied at MCC or switchboard where multiple passive filters may not be practical
- Can reduce THD to less than 5%



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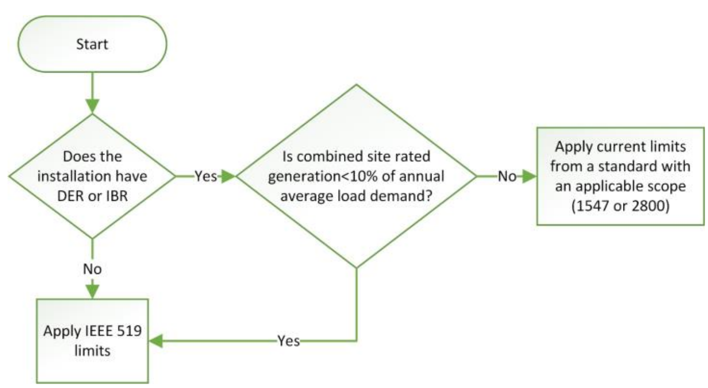
Additional harmonic standards

- New decision tree in IEEE Std. 519-2022 directs users to IEEE Std. 1547-2018 or IEEE Std. 2800-2022
- 1547-2018: Applies to Distributed Energy Resources (DER) connected to electric power systems
- 2800-2022: Applies to Inverter-Based-Resources (IBR) connected to transmission systems
- Inverter-based resources are a subset of Distributed Energy Resources



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Comparing IEEE Standards 519-2022, 1547-2018

519-2022

Table 2—Current distortion limits for systems rated 120 V through 69 kV

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

1547-2018

Table 26—Maximum odd harmonic current distortion in percent of rated current (I_{rated})[a]

Individual odd harmonic order h	$h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h < 50$[109]	Total rated current distortion (TRD)
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

[a] I_{rated} = the DER unit rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA).

Table 27—Maximum even harmonic current distortion in percent of rated current (I_{rated})[a]

Individual even harmonic order h	$h = 2$	$h = 4$	$h = 6$	$8 \le h < 50$
Percent (%)	1.0	2.0	3.0	Associated range specified in Table 26

[a] I_{rated} = the DER unit rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA).

- The limits on odd current harmonics in IEEE Std. 519-2022 Table 2, and IEEE Std. 1547-2018 Table 26 are identical. These limits will apply in most applications. (Where DER is connected to a utility distribution system.)
- Primarily, the decision tree in IEEE Std. 519-2022 clarifies when the generation limits apply. (When DER capacity ≥10% of annual average load demand)

Additional harmonic standards

- EN 50160 – “Voltage Characteristics Of Electricity Supplied By Public Distribution Systems”
  - Voltage at the PCC only
  - Addresses harmonics, sags, swells, etc.
  - May be incorporated in power quality recorders
  - Describes 95% conditions
  - Operation at minimum requirements is not likely to be acceptable to customers.

The IEC standards (See PSQ pg. 313+)

- IEC – International Electrotechnical Commission
  - Main organization developing power quality standards for the international community
- IEC standards have six parts:
  1. General – definitions, terms
  2. Environment – description and characteristics
  3. Limits – Allowable disturbances caused by equipment
  4. Testing and measurement techniques – guidelines for measurement equipment and test procedures
  5. Installation and mitigation guidelines – application of filters, surge suppressors, etc.
  6. Generic and product standards – define equipment immunity levels

Standards

- Standards continue to become more international – several IEEE standards reference IEC standards.
- IEEE Power Engineering Society Power Quality Subcommittee
  - Works to coordinate international power quality standards including harmonic standards
  - In some cases identical standards are issued from multiple organizations now
    - ANSI/ISA-61010-1 is practically identical to IEC 61010-1, CSA C22.2 No. 1010.1, and UL 61010-1

Why have harmonic (and other) standards?

- Improve compatibility between the power system and end-user equipment
- For utilities
  - Provides measurable limits that can be used as the basis for system design
- For equipment manufacturers
  - Describes the equipment's electrical environment
  - Helps manufacturers design equipment to operate acceptably

Next time…

- Start long-duration voltage variations
- Midterm discussion