ECE 528 – Understanding Power Quality

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

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Lecture 11

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Today…

- Homework 3 overview
- Harmonics
  - Impacts on capacitors and transformers
  - Transformer Derating
  - Interharmonics

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Lecture 11

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HW3, Prob. 2

- (See PSQ section 5.7.3.(pg. 225))
  - Saturable reactance is not linear
  - Relationship between V and I changes
  - Effect may be pronounced during primary overvoltages
  - An interesting paper on the subject:

  Modeling of Harmonic Sources – Magnetic Core Saturation, by Yilu Liu and Zhenyuan Wang

  https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=a72146cf9bfd3da69bab9b6f09af42b48699c427

HW3, Prob. 3

- Fundamental currents of VFD and total load are different.
- Table includes drive current harmonics in percent.
- Assume the resistive load only adds 60Hz current.
  - 3.1 – THD for the Variable Frequency Drive ONLY
  - 3.2 – TDD for the whole load; VFD + resistive load
  - 3.3 – ALL harmonics, in amps. Percent is O.K. in addition but not instead, and percent of what? (Also, don't forget even harmonics)
  - 3.4 – Comply with IEEE-519? Yes or no, and if not, include a list of non-compliant harmonics. Remember:
    - TDD is also limited by IEEE-519
    - Harmonic limits change with even/odd and with increasing harmonic number – the footnotes for IEEE-519 Table 2 are important.

Effects of harmonic distortion

- Capacitors
  - Overheating
  - Blown fuses
  - May provide a path to the neutral for triplen harmonics
- Transformers
  - Harmonic current and voltage distortion will contribute to transformer heating

Derating transformers serving non-linear loads
(PSQ 5.10.2, FPQ 6.6.2 - Based on IEEE Standard C57.110)

- Corrections to PSQ text:
  - p243, Mid-page: “The analysis represented in this table…” refers to table 6.5, page 305.
  - Also, eq. 5.30 and 5.31 are wrong; K-factor is not the same as F_{HL} (Harmonic Loss Factor) See FPQ eq. 6.64 and 6.68 for correct definitions.
- Corrections to FPQ text:
  - Table 6.4 on p229; second “Dry” should be “oil- filled” See PSQ table 5.2

  Note: table 6.6, FPQ p231 will be useful for the midterm – coming soon.

Derating transformers serving non-linear loads

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- Transformer losses due to harmonic currents:
  - I^2R losses – increased RMS current = more losses
  - Eddy-Current Losses – increase with the square of the current frequency
  - Other Stray Losses – not as significant as I^2R losses and eddy-current losses – these losses are due to the currents induced in the transformer parts other than the windings – such as the case.

Derating transformers serving non-linear loads
FPQ pg 226-231

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- Total load losses (heating) is: (eq. 6.56)

$$P_{LL} = P_{I^2R} + P_{EC} + P_{OSL}$$

We'll ignore the Other Stray Losses

- At rated full load current (I_R): (eq.6.57)

$$P_{LL-R} = P_{I^2R-R} + P_{EC-R}$$

The "-R" indicates rated conditions.

Derating transformers serving non-linear loads

- We'll switch to per-unit analysis with bases of:
  - Power: P_{I^2R-R} Current: I_R
- The loss equation becomes:

$$P_{LL-R}(pu) = 1 + P_{EC-R}(pu)$$

- The per-unit eddy current loss factor is a constant that we can get from tables or the transformer manufacturer. See FPQ table 6.4, p. 229.

Derating transformers serving non-linear loads

- Changes to losses with harmonics: P_{I^2R}

$$P_{I^2R} = P_{I^2R-R} \cdot \sum_h \left(\frac{I_h}{I_R}\right)^2$$

FPQ Eq. 6.59 - The summation is a factor that increases the RMS value of the current in the I^2R losses based on harmonic content. I_R is rated current.

- In per-unit...

$$P_{I^2R}(pu) = \sum_h \left[I_h^2(pu)\right]$$

h= 1 to 25 typically
<u>note: the fundamental is included</u>

Derating transformers serving non-linear loads

- Changes to losses with harmonics: P_{EC}

$$P_{EC} = P_{EC-R} \cdot \sum_h \left[\left(\frac{I_h}{I_R} \right)^2 \cdot h^2 \right]$$

The summation is a factor that increases the eddy current losses by the square of the frequency causing the losses; it's called the **K-factor**.

- In per-unit…

$$P_{EC}(pu) = P_{EC-R}(pu) \cdot \sum_h \left[\left[I_h(pu) \right]^2 \cdot h^2 \right]$$

Derating transformers serving non-linear loads

- A little rearranging…

$$P_{LL}(pu) = P_{I^2R}(pu) + P_{EC}(pu)$$

$$P_{LL}(pu) = \sum_h \left[I_h^2(pu) \right] + P_{EC-R}(pu) \cdot \sum_h \left[\left[I_h(pu) \right]^2 \cdot h^2 \right]$$

$$P_{LL}(pu) = \sum_h \left[I_h^2(pu) \right] \cdot \left[1 + P_{EC-R}(pu) \cdot \frac{\sum_h \left[\left[I_h(pu) \right]^2 \cdot h^2 \right]}{\sum_h \left[I_h^2(pu) \right]} \right]$$

F_{HL} – the harmonic loss factor for eddy currents

Derating transformers serving non-linear loads

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- F_{HL} – the harmonic loss factor for eddy currents:

$$F_{HL} = \frac{\sum_h \left[\left[I_h(pu) \right]^2 \cdot h^2 \right]}{\sum_h \left[I_h^{\,2}(pu) \right]}$$

See other forms of this equation in eq. 6.64, pg. 228, FPQ.

The harmonic loss factor F_{HL} for eddy currents relates the eddy current losses with harmonics to the eddy current losses without harmonics.

Derating transformers serving non-linear loads

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- We're trying to keep the heating with the distorted load current less than or equal to normal heating at rated load without harmonics:

$$\underbrace{\left[\sum_h \left[I_h^{\,2}(pu) \right] \right] \cdot \left[1 + P_{EC-R}(pu) \cdot F_{HL} \right]}_{\text{Per-unit losses with harmonics}} \le \underbrace{1 + P_{(EC-R)}(pu)}_{\text{Rated per-unit losses without harmonics}}$$

Per-unit losses with harmonics

Rated per-unit losses without harmonics

Derating transformers serving non-linear loads

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- More rearranging of equations. Also taking the square root of each side to get the per-unit RMS current gives us the Derating Factor:

$$I_{max}(pu) = \sqrt{\sum_h \left[I_h^2(pu) \right]} = \sqrt{\frac{1 + P_{EC-R}}{1 + P_{EC-R} \cdot F_{HL}}}$$

The derating factor is a percentage or per-unit value that represents the reduced capacity of the transformer due to the additional heating caused by the harmonic content of the current. (6.68 in FPQ)

Derating transformers serving non-linear loads

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- Example 6.7 from FPQ p. 229. Rated current is 600A. Fundamental happens to be 400A.
  - From table 6.4: $P_{EC\_R} := 0.15$
  - From table 6.6: $F_{HL} := \frac{9.9114}{1.596}$ $\quad F_{HL} = 6.21$

Derating transformers serving non-linear loads

- The result:

$$\text{Derating} = \sqrt{\frac{1 + P_{EC\_R}}{1 + F_{HL} \cdot P_{EC\_R}}}$$

$$\text{Derating} = 0.7716$$

The "allowable current" calculation in P.U. translates directly to a derating factor

- For a current with the harmonic spectrum described in FPQ table 6.5, the transformer should be derated to 77.16% of its nameplate capacity.

Derating transformers serving non-linear loads

- Another way to compensate for distorted load current – The K-factor (FPQ p. 231):

$$K\_factor = \frac{\sum_h \left(I_h^2 h^2\right)}{I_R^2}$$

K-factor is a multiplier for the eddy-current losses in the transformer.

- To use the K-factor, we compute the K-factor for a given current and select a K-rated transformer accordingly.
- Note: K-factor depends on the magnitude of the current – we can reduce K by reducing overall loading; in effect derating the transformer.

K-factor's relationship to derating

$$\sum_h \left[I_h^2(pu)\right]\cdot\left[1 + P_{EC-R}(pu)\cdot F_{HL}\right] \le 1 + P_{(EC-R)}(pu)$$

From slide 12 (eq. 6.67 in FPQ)

Multiply through

$$\sum_h \left[I_h^2(pu)\right] + P_{EC-R}\cdot(pu)\cdot\left[\sum_h \left[I_h^2(pu)\right]\cdot\left[\frac{\sum_h \left[I_h^2(pu)\cdot h^2\right]}{\sum_h \left[I_h^2(pu)\right]}\right]\right] \le 1 + P_{(EC-R)}(pu)$$

Cancel like terms

$$\sum_h \left[I_h^2(pu)\right] + P_{EC-R}\cdot(pu)\cdot K\_factor \le 1 + P_{(EC-R)}(pu)$$

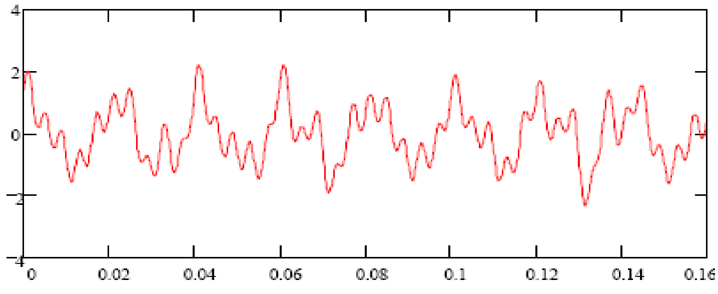
Other impacts

- Motors (review)
  - For motors, the impact of harmonic voltages is similar to negative sequence fundamental frequency voltages – heating
- Telecommunication systems
  - Higher frequency currents on the power system will more easily couple to nearby communication circuits

Interharmonics (PSQ only)

IEC-1000-2-1 definition:

"Between the harmonics of the power frequency voltage and current, further frequencies can be observed which are not an integer of the fundamental. They can appear as discrete frequencies or as a wide-band spectrum."



From: "Interharmonics in Power Systems" – IEEE Interharmonic Task force, Cigré 36.05/CIRED WG 2

Interharmonics – (PSQ only)

- Issues:
  - Measurement – requires multiple fundamental cycles
  - Heating – similar to regular harmonic currents
  - Light flicker – Low-frequency interharmonics can create noticeable light flicker

Harmonics - Division of responsibility

- Utility
  - Limit voltage distortion: IEEE 519-2022, Table 1
    - Individual harmonic limits (% of nominal fundamental)
    - <u>THD</u> limits
      - IEEE-519-2014 increased the allowable voltage distortion from the 1992 edition.
    - How:
      - Monitor system and users
      - Apply current distortion limits
      - Avoid resonances
      - Educate users

Division of responsibility

- End-users
  - Limit current distortion: IEEE 519-2014, Tbl. 2-4
    - Individual harmonic limits (% of maximum fundamental demand current)
    - <u>TDD</u> limits
      - Limits based on short-circuit ratio (I_{SC}/I_L) and service voltage
    - How:
      - Notify utility of new non-linear load, and install filters if necessary
      - Report possible harmonic problems
      - Notify utility of capacitor bank installations

The point of common coupling (PCC)

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- Most downstream point in the system where another customer can be served
- Each PCC has, or could have at least two customers
- Point where harmonic limits apply
- Applying limits at the PCC benefits customers
  - Prevents interference with other customers
  - Only requires mitigation necessary to limit interference with others
- Utilities may apply certain limits downstream of the conventional PCC
  - To protect transformers for example

Some PCC examples

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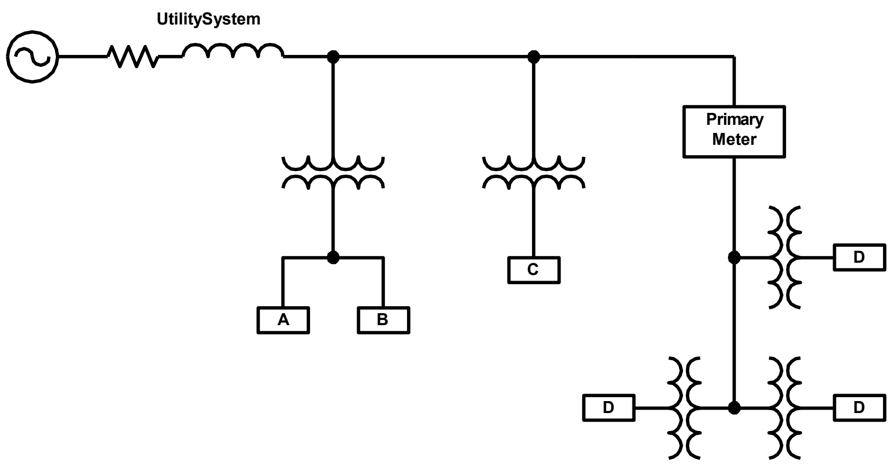

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Coming up…

- Mitigation
- More Examples