University of Idaho
College of Engineering

ECE 528 – Understanding Power Quality

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

Paul Ortmann
portmann@uidaho.edu
208-733-7972 (voice)

Lecture 21

Today…

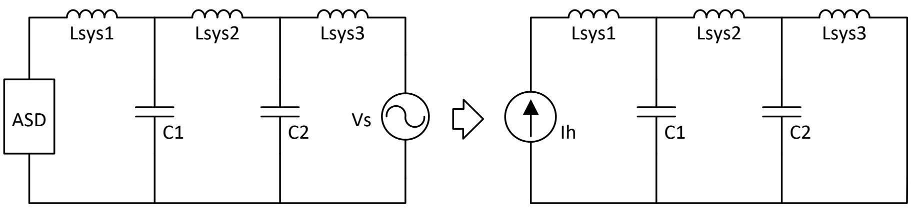
- Harmonics
  - System response
  - Parallel and series resonance
  - Impacts on capacitors and transformers
  - Transformer Derating
  - Interharmonics

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 resonance (FPQ pgs 246-249)

- There can be multiple resonant frequencies:



Basic system with two capacitors and an ASD

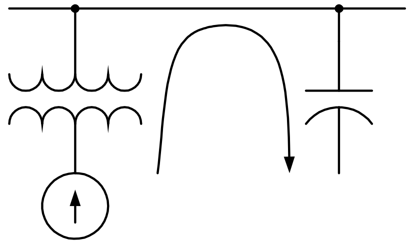
Thevenin Equivalent for analyzing contribution of ASD

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

University of Idaho

Series resonance (FPQ pgs 250-251)

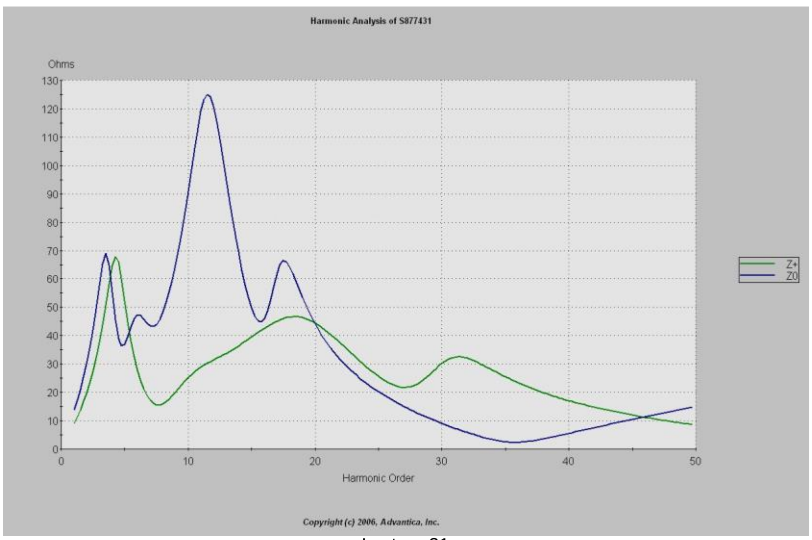
- Created by series combination of transformer and capacitor
- May affect customers with no non-linear load
- May damage utility capacitors near customers with non-linear loads



Lecture 21 5

University of Idaho

A real-world example



Lecture 21 6

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 (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 is a good example for HW4.

Derating transformers serving non-linear loads

- 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.

University of Idaho

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

- 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.

University of Idaho

Derating transformers serving non-linear loads

- We'll switch to per-unit analysis with bases of:
  - Power: P_{I^2R-R} Current: $\mathbf{I_R}$
- 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.

University of Idaho

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…

h= 1 to 25 typically

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

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…

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

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

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

Derating transformers serving non-linear loads

- 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

- 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

- 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

- Example from FPQ p. 230.
  - From table 6.4:

$$P_{EC\_R} := 0.15$$

  - From table 6.6:

$$F_{HL} := \frac{9.9114}{1.596} \qquad F_{HL} = 6.21$$

University of Idaho

Derating transformers serving non-linear loads

- The result:

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

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

$$\text{Derating} = 0.7716$$

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

University of Idaho

Derating transformers serving non-linear loads

- Another way – The K-factor (FPQ p. 231):

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

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

- Using 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.

University of Idaho

K-factor's relationship to derating

From slide 16 (eq. 6.67 in FPQ)

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

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

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

University of Idaho

Other impacts

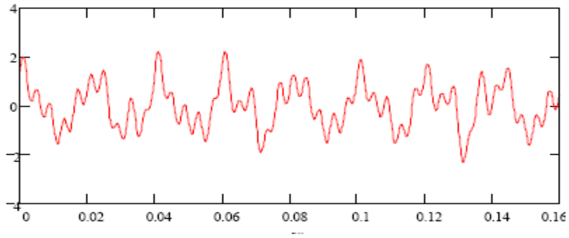
- Motors
  - For motors, the impact of harmonic voltages is similar to that of negative sequence fundamental frequency voltages – heating
- Telecommunication systems
  - Higher frequency currents on the power system will more easily couple to nearby communication circuits

University of Idaho

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

University of Idaho

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