NEPSI

Northeast Power Systems, Inc.

Medium-Voltage Metal-Enclosed Products

Power Capacitor Banks, Harmonic Filter Banks,
actiVAR™, & Surge Protection

Harmonic Analysis – Knowing the Basics Is Essential

Presented by Paul Steciuk
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actiVAR armorVAR armorVAR

Harmonic Analysis – Knowing the Basics Is Essential
- Summary of Presentation -

Harmonic analysis tools such as ETAP, EasyPower, CYME, SKM, PSCAD, and others are indispensable tools that aid engineers with the evaluation and mitigation of the negative impact of non-linear loads on industrial and utility power systems. However, when these tools are presented with bad input data or the program output is interpreted improperly, they lead to incorrect system design. Starting at Ohms Law and the creation of equivalent circuits, this presentation demystifies the topic of harmonics, harmonic resonance, and harmonic filtering. It provides the fundamental knowledge that is necessary to effectively perform harmonic analysis, to do “back-of-the-envelope calculations”, interpret harmonic reports, and evaluate mitigation strategies.

After completion, the attendees will understand how harmonic studies are conducted, what harmonic are, where they come from, what harmonic resonance is, their impact on the power system, harmonic filtering, harmonic current amplification, and much more. The attendees acquire the necessary knowhow to verify and evaluate vendor recommendations, harmonic analysis reports, and filter designs. The presenter encourages discussion and questions on such topics as input data, extent of modelling, impedance data, harmonic load modeling, modeling of stray capacitance, 519 compliance, harmonic measurement procedures, interharmonics, and non-characteristic harmonics, data validation, model validation, filter design, resonance, and interpretation of program outputs an more.

If you are involved with the application of non-linear loads (rectifiers, LCI drives, ASD/VFD drives, active-front-end drives, high-pulse drives, “IEEE 519 Compliant”, Cycloconverters), harmonic filters, or power factor correction, consider coming to this informative presentation by a leading industry expert.

Harmonic Analysis – Presentation Outline

Corporate Introduction (5 Minutes to 10 Minutes) – Please consider having Procurement attend the portion of the presentation.

- NEPSI's Products and Services
    - Medium-voltage metal-enclosed reactive compensation products
    - Services
        - Studies
        - Maintenance / startup and commissioning services
- Breaking the package

Harmonic Analysis – Knowing the Basics is Essential

- Why perform harmonic analysis
- Steps to conducting harmonic analysis
- Harmonic current sources
- Analysis basics
    - Simple system (source impedance + transformer)
        - Equivalent Circuit
        - Calculation of harmonic voltage and current distortion (ohms law)
        - Impedance scan and interpretation
- Simple System with addition of capacitance
    - Equivalent circuit
    - Impact on Impedance Scan
        - Resonance and impact to voltage distortion

Harmonic Analysis – Presentation Outline (Continued)

Harmonic Analysis – Knowing the Basics is Essential (continued)

- Tuning around resonance – can it be done?
- Interpretation of impedance scan
  - Sensitivity analysis (short circuit level, component tolerances, etc.)
- Harmonic current amplification

- Adding capacitors as harmonic filters
  - Equivalent circuit
  - Impact on impedance scan
  - Impact on voltage and current distortion
    - Tuned versus de-tuned capacitor banks
- Multi-tuned harmonic filter banks
  - Resonance concerns
  - Sequence of operation
- Other types of filters (C-HP, HP)

NEPSI Resources

- Webpage (spreadsheet tools, calculators, product literature, guide-form specifications, how-to-videos, and more)
- Reactive power working sessions

Questions/Answers

Background of Presenter

Paul B. Steciuk is president and co-founder of **Northeast Power Systems, Inc. (NEPSI)**, the leading global supplier of medium-voltage metal-enclosed power capacitor banks and harmonic filter systems. Mr. Steciuk has grown the company and provided engineering and product support to owners and operators of small and large industrial, commercial, renewable, and utility power systems through NEPSI for over 20 years.

With over 30 technical articles and white papers to his credit, Mr. Steciuk is an expert in harmonic analysis, filter design and application, power system analysis, and manufacturing design.
Mr. Steciuk has previous experience as a power system engineer at Power Technologies, Inc. (PTI), located in Schenectady, NY where he was responsible for various power system studies including system-wide voltage sag studies, harmonic analysis and filter design studies, load-flow, short-circuit, protective coordination, and transient analysis studies.

He also worked as an application and design engineer at Commonwealth Sprague Capacitor, Inc. (CSCI), located in North Adams, MA. designing and developing low voltage automatic power factor correction equipment and harmonic filters.

Born in Troy, NY, Mr. Steciuk received his B.S. and M.E. degrees in Electric Power Engineering from Rensselaer Polytechnic Institute (RPI), Troy, NY.

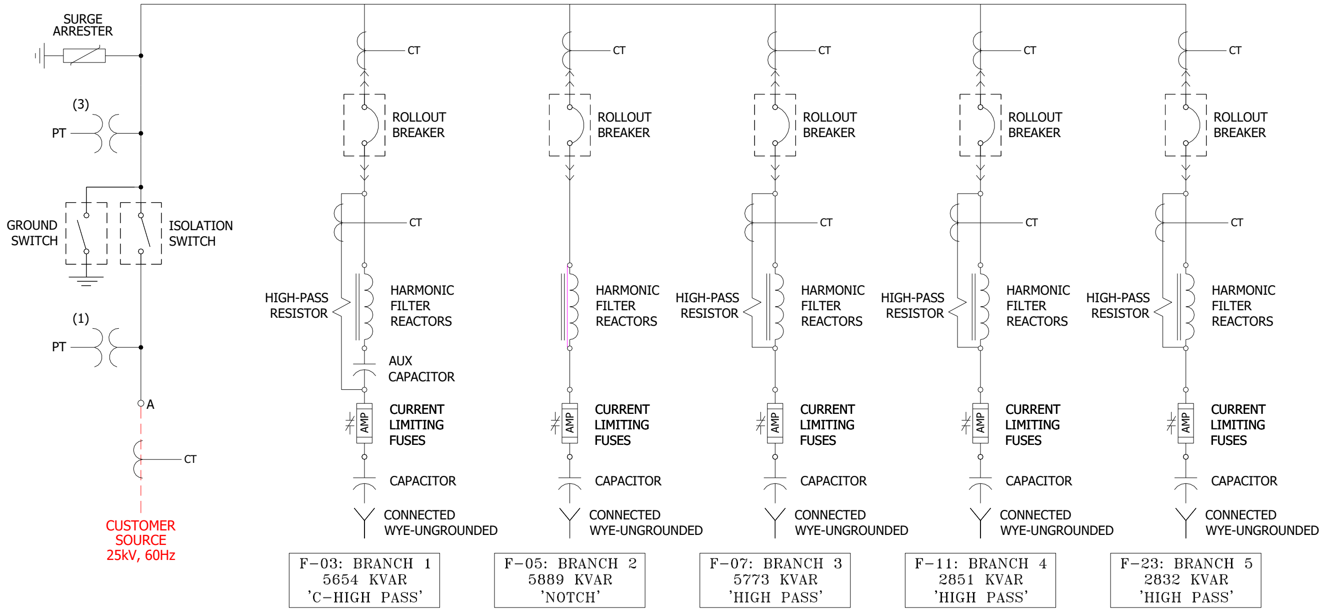
NEPSI - Background

- Established in 1995
- Based in Queensbury, NY
- Key products designed and manufactured by NEPSI
  - Medium-voltage metal-enclosed products (2.4kV – 38kV) 200 kV BIL Max
    - Shunt Power **Capacitor Banks** (capacitive vars)
    - **Harmonic Filter Banks**
    - Shunt Reactor Banks (inductive vars)
    - Hybrid Shunt Capacitor & Shunt Reactor Banks
    - actiVAR™ – Fast Switching Capacitor Banks/Harmonic Filter Banks (2.4kV – 13.8kV) for motor start – an alternate to large VFD drives and RVSS
    - Medium Voltage Surge Protection Products
      - RC Snubbers
      - Motor Surge Protection
      - Medium-Voltage Transient Voltage Surge Protection
- Service
  - Startup | Commissioning | Maintenance
  - Power System Studies
    - Harmonic Analysis, Power Factor, Motor Start

Large Harmonic Filter Systems Designed & Manufactured by NEPSI

Large Harmonic Filter System 1 of 2 (1-line to follow)

Large Harmonic Filter One-Line Diagram



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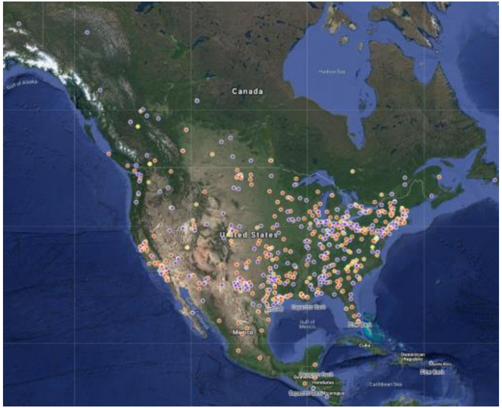
Background

NEPSI Sells Into All Major Markets

- Mining (copper, gold, diamond, oil sands, limestone, lithium, rare earth metals)
- Renewable energy (wind & solar power)
- Oil/Gas, Petro-Chemical
- Electric Utilities (large IOU’s, electric cooperatives, municipalities)
- Steel
- Pulp & Paper
- Institutions (hospitals, universities, military bases, data centers, financial institutions)
- Private Label – Supplier of product to nearly all of the “majors”
- Others
  - semiconductor, scrap recycling, pharma, waste water

Largest Installed Based On The Globe



North & Central America

South America

Africa, Asia, Europe, Australia

With an installed base of over 2000 systems over the last 24 years (more than 140 in mining and 800 in Oil/Gas) **NEPSI** is the leading world supplier of medium-voltage metal-enclosed capacitor banks and harmonic filter banks

NEPSI also brand labels for ABB, GE, Schneider, Eaton and other large electrical brands

Configuration Options – Metal-Enclosed / Open-Air

Metal-Enclosed

Open-Air

When all costs are considered, including engineering & procurement, integration, site preparation, installation, commissioning, maintenance, and liability, **the Metal-Enclosed configuration provides the lowest cost of ownership**

Configuration Options – Metal-Enclosed / E-House

Metal-Enclosed Configuration


E-House Configuration

Metal-enclosed laser focused, elegant solution that avoids the complex, ancillary requirements (and associated costs) of local and national building codes inherent with the e-house configuration.

The streamlined approach to power-factor correction and harmonic filtering.

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Harmonic Analysis
Knowing the Basics is Essential

Presented by Paul Steciuk
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Technical Presentation

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Why Perform Harmonic Analysis?

- Determine compliance with harmonic standards (IEEE 519)
  - Existing systems under expansion or change
  - New facilities
- Calculation of: Voltage Distortion | Current Distortion
- Evaluate resonance concerns
  - Due to the addition of shunt power capacitors
  - Due to cable capacitance (windfarm collector system resonance)
- Evaluate filter design & performance

Steps in Performing Harmonic Analysis & Filter Design Studies

Create System Model
- Impedance Data
- Harmonic Injection Data (by measurement) (by calculation)
- Capacitor Banks / Line | Cable Capacitance

Validate System Model
- Load Flow Analysis
- Short Circuit Analysis
- Basic Calculation Methods
- Comparison with Measurement Data

Impedance Scan Analysis
- Determine Resonance Frequencies
- Determine Sensitivity of System to Change
- Confirm Filter Design

Calculate Distortion
- Current Distortion at PCC (IEEE 519)
- Voltage Distortion Throughout Facility

Filter Design
- Type of Filter, Rating, # of Steps, & Performance
- Determine Filter Parameters
- Equipment Requirements

  Disconnecting Switching Protection Control

  Spec Development

Harmonic Analysis Report
- Report Findings
- Report Input Data & Assumptions
- Filter Design/Spec

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What are Harmonics? - Background

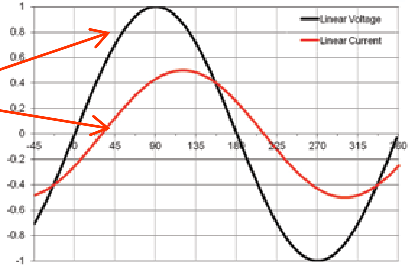
Linear loads

- Impedance is constant with the applied voltage
  - Resistive heaters
  - Incandescent lights

Non-Linear Loads

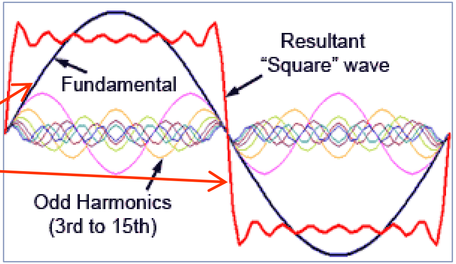
- Impedance changes with applied voltage
  - Variable frequency drives (VFD’s/AFD’s)
  - Cycloconverters
  - LCI drives
  - Rectifiers
  - Arc furnace and arc welding equipment

Linear load Waveform



Current waveform looks like the voltage waveform

Non-Linear load Waveform



Current does not look like the voltage waveform

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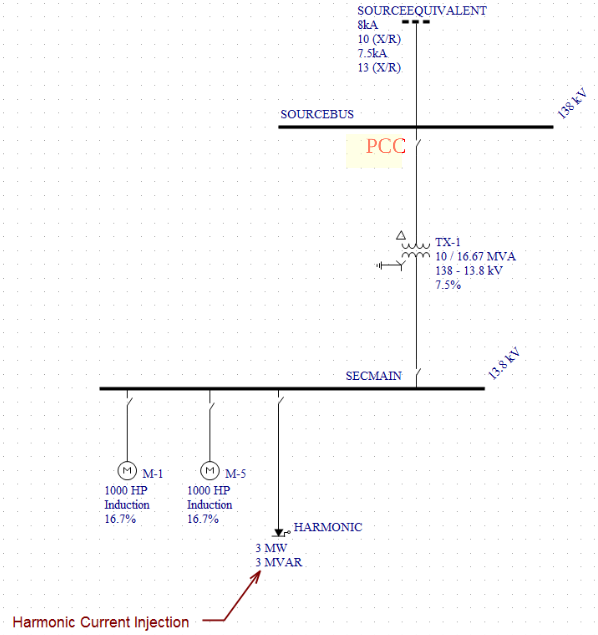
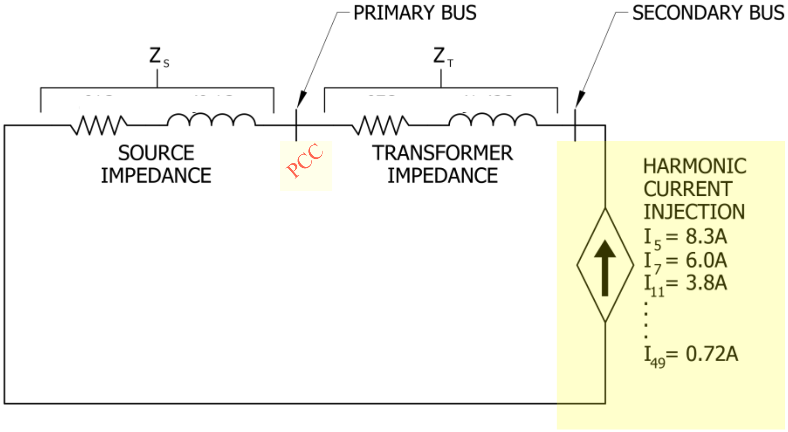
Equivalent Circuit – What the Program Does





- Above equivalent circuit shows ohms at 13.8kV and 60Hz
- Can also be done using Per Unit System
- There is one impedance network for each harmonic
- Remember: $X_L = j2\pi fL$ & $X_C = \frac{1}{j2\pi fC}$

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IEEE 519-2014, Voltage Distortion Limits at Point-of-Common Coupling (PCC)

5.1 Recommended harmonic voltage limits

At the PCC, system owners or operators should limit line-to-neutral voltage harmonics as follows:

— Daily 99th percentile very short time (3 s) values should be less than 1.5 times the values given in Table 1.

— Weekly 95th percentile short time (10 min) values should be less than the values given in Table 1.

All values should be in percent of the rated power frequency voltage at the PCC. Table 1 applies to voltage harmonics whose frequencies are integer multiples of the power frequency.

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

Eq. Circuit

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IEEE 519-2014, Current Distortion Limits at Point-of-Common Coupling (PCC)


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IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems
IEEE Power and Energy Society
Sponsored by the Transmission and Distribution Committee
IEEE Std 519™-2014 (Revision of IEEE Std 519-1992)
IEEE
3 Park Avenue
New York, NY 10016-5997
USA

5.2 Recommended current distortion limits for systems nominally rated 120 V through 69 kV

The limits in this subclause apply to users connected to systems where the rated voltage at the PCC is 120 V to 69 kV. At the PCC, users should limit their harmonic currents as follows:

— Daily 99th percentile very short time (3 s) harmonic currents should be less than 2.0 times the values given in Table 2.

— Weekly 99th percentile short time (10 min) harmonic currents should be less than 1.5 times the values given in Table 2.

— Weekly 95th percentile short time (10 min) harmonic currents should be less than the values given in Table 2.

All values should be in percent of the maximum demand current, I_L. This current value is established at the PCC and should be taken as the sum of the currents corresponding to the maximum demand during each of the twelve previous months divided by 12. Table 2 applies to harmonic currents whose frequencies are integer multiples of the power frequency.

Eq. Circuit

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IEEE 519-2014, Current Distortion Limits at Point-of-Common Coupling (PCC) - Continued


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USA

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 (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	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]Even harmonics are limited to 25% of the odd harmonic limits above.

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

[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

where

I_{sc} = maximum short-circuit current at PCC

I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

Eq. Circuit

IEEE 519-2014, Current Distortion Limits at Point-of-Common Coupling (PCC) - Continued


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5.3 Recommended current distortion limits for systems nominally rated above 69 kV through 161 kV

The limits in this subclause apply to users connected to systems where the rated voltage V at the PCC is 69 kV < $V \leq$ 161 kV. At the PCC, users should limit their harmonic currents as follows:

— Daily 99th percentile very short time (3 s) harmonic currents should be less than 2.0 times the values given in Table 3.

— Weekly 99th percentile short time (10 min) harmonic currents should be less than 1.5 times the values given in Table 3.

— Weekly 95th percentile short time (10 min) harmonic currents should be less than the values given in Table 3.

All values should be in percent of the maximum demand current, I_L. This current value is established at the PCC and should be taken as the sum of the currents corresponding to the maximum demand during each of the twelve previous months divided by 12. Table 3 applies to harmonic currents whose frequencies are integer multiples of the power frequency.

Eq. Circuit

IEEE 519-2014, Current Distortion Limits at Point-of-Common Coupling (PCC) - Continued

Table 3—Current distortion limits for systems rated above 69 kV through 161 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{sc}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20[c]	2.0	1.0	0.75	0.3	0.15	2.5
$20 < 50$	3.5	1.75	1.25	0.5	0.25	4.0
$50 < 100$	5.0	2.25	2.0	0.75	0.35	6.0
$100 < 1000$	6.0	2.75	2.5	1.0	0.5	7.5
> 1000	7.5	3.5	3.0	1.25	0.7	10.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

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

[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

where

I_{sc} = maximum short-circuit current at PCC

I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

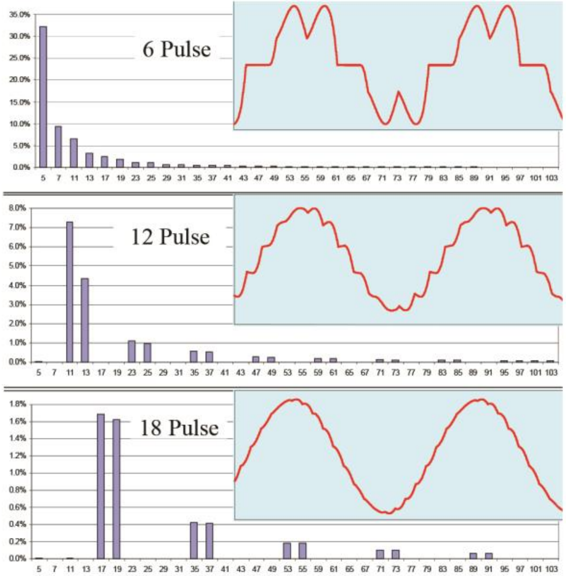
Eq. Circuit

Harmonic Current Injection – Where To Obtain Values?

Harmonic Currents Injection

- Normally modeled as ideal current source (magnitude / frequency)
- Obtained through measurement on existing systems
- Obtained from supplier of non-linear load device
    - Should be required as condition of purchase order for drive, rectifier, cycloconverter, arc furnace, etc.
- Assumed – Use IEEE reference values
    - Tables from standard
    - Value based on pulse-number

$h = P.n \pm 1$ (1)
where:
n = an integer (1, 2, 3, 4… ∞).
h = harmonic order.
P = the number of pulses of the rectifier.



Eq. Circuit

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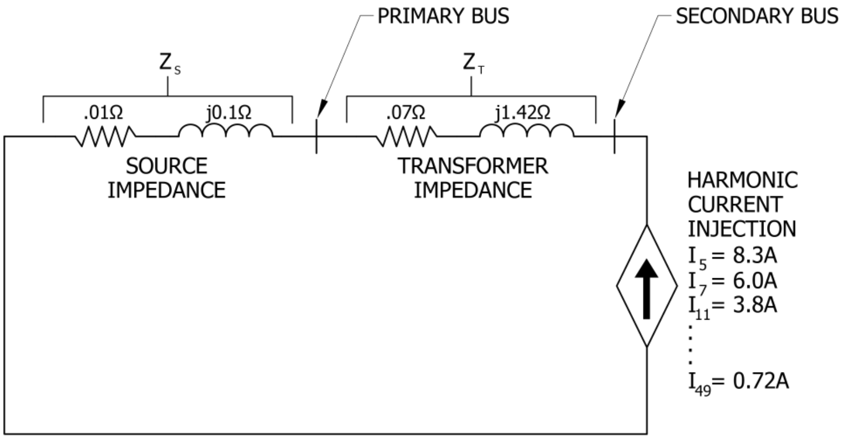
Equivalent Circuit – With Impedance Values



60Hz Network, ohms at 13.8kV

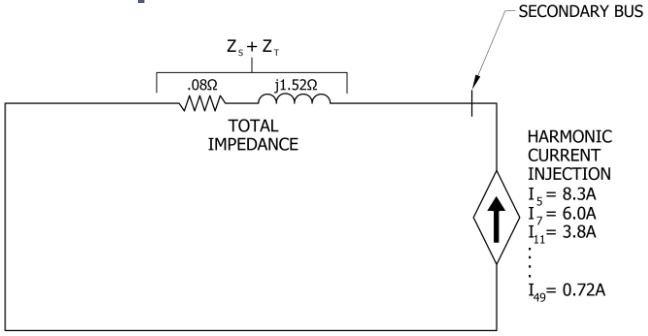
Calculation Method for Z_S
8kA at 138kV = 1909 MVAsc
X_S at 13.8kV ≈ 13.8^2/1909 ≈ 0.1 ohms

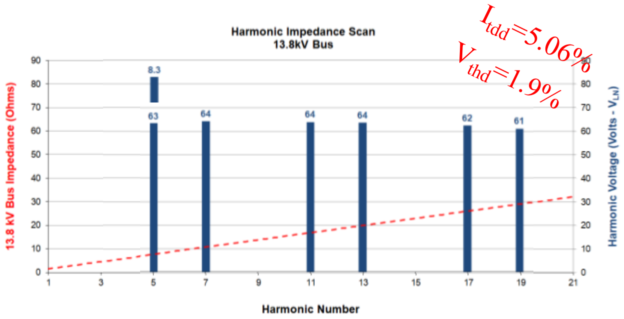
Calculation Method for Z_T
10 MVA Transformer with 7.5% Impedance

Base Impedance = 13.8^2/(10 MVA) = 19.04 ohms
X_T ≈ 19.04 X 0.075 ≈ 1.42 ohms

R values based on X/R ratio. They can be considered constant with frequency. In reality, harmonic programs use equations for skin effect and increase resistance at higher frequencies

Equivalent Circuit – Reduced to A Single Impedance





Equivalent Network – Reduced to Single Impedance

- With no capacitors in network, impedance varies linearly with frequency
- Voltage calculation at each frequency is a matter of multiplying harmonic current by harmonic impedance. Calculated voltage is a line-to-neutral value.

- $I_{thd} = \sqrt{\frac{I_5^2+I_7^2+I_{11}^2+I_{13}^2+I_{17}^2+\cdots I_n^2+}{I_1^2}}$
- $I_{tdd} = \sqrt{\frac{I_5^2+I_7^2+I_{11}^2+I_{13}^2+I_{17}^2+\cdots I_n^2+}{I_{1\ demand}^2}}$
- $V_{thd} = \sqrt{\frac{V_5^2+V_7^2+V_{11}^2+V_{13}^2+V_{17}^2+\cdots V_n^2+}{V_1^2}}$

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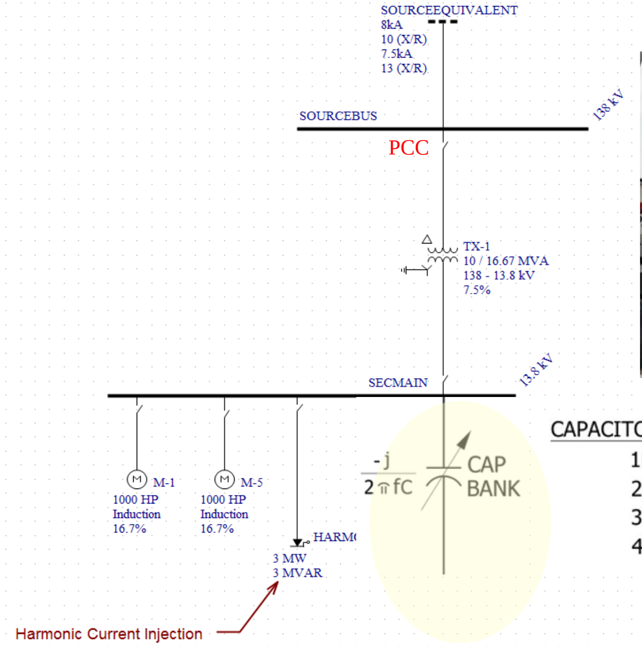
What Happens When We Add A Capacitor Bank To The System?



CAPACITOR REACTANCE @ 13.8kV

1MVAR=-j 190.4Ω

2MVAR=-j 93.1Ω

3MVAR=-j 63.5Ω

4MVAR=-j 47.6Ω

NEPSI Metal-Enclosed Capacitor Bank Being Installed At A Gas Plant

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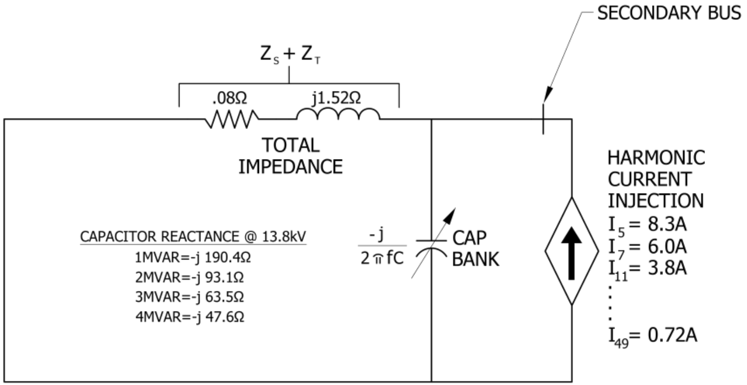
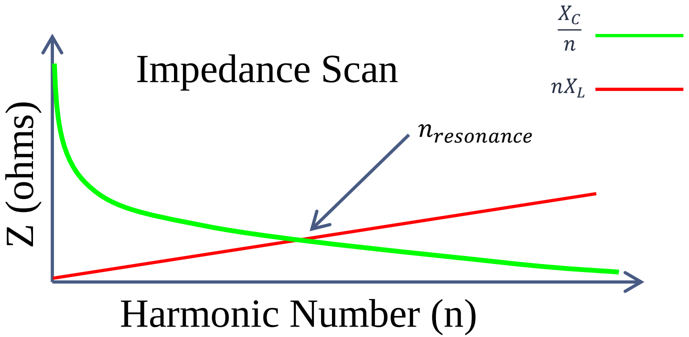
Equivalent Circuit With Capacitor Bank



$$X_c = \frac{kV_{LL}^{\;2}}{MVAR_{3\emptyset}}(ohms)$$

$$n_{resonance} = \sqrt{\frac{X_C}{X_L}} = \sqrt{\frac{KVA_{SC}}{kvar_{cap\ bank}}}$$

- Adding capacitors to a power system results in resonance.
- There can be one or more resonances in a network.
- Resonance occurs where $\frac{X_C}{n} = nX_L$



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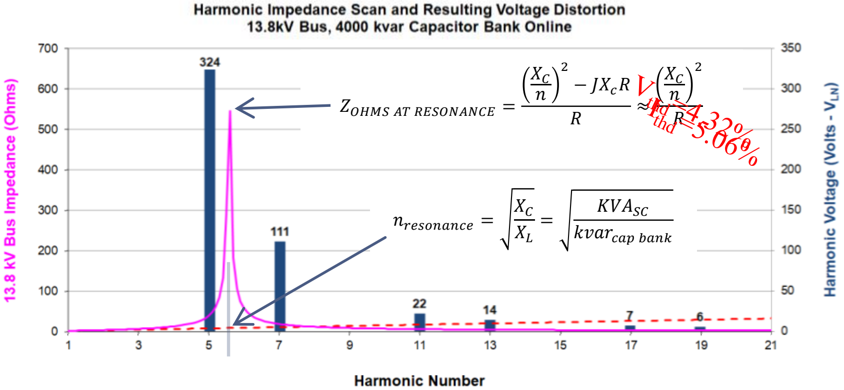
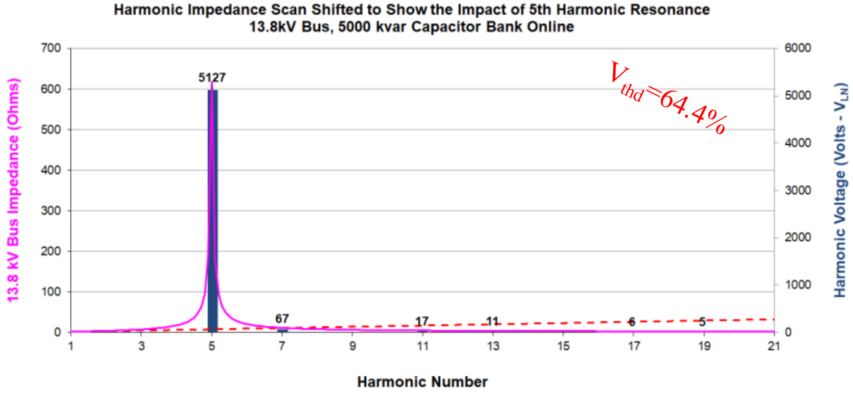
Impedance Scan Showing Resonance– 4 MVAR Capacitor Bank



$$n_{resonance} = \sqrt{\frac{X_C}{X_L}} = \sqrt{\frac{KVA_{SC}}{kvar_{cap\ bank}}} \approx \sqrt{\frac{47.6}{1.52}} \approx 5.59$$

- On simple systems (one capacitor and a purely inductive source impedance, the resonance can be estimated with formula shown on impedance scan.
- Peak of resonance is determined by resistance of network at resonance frequency.
- Resonance causes high voltage distortion and high current distortion in presence of harmonic current

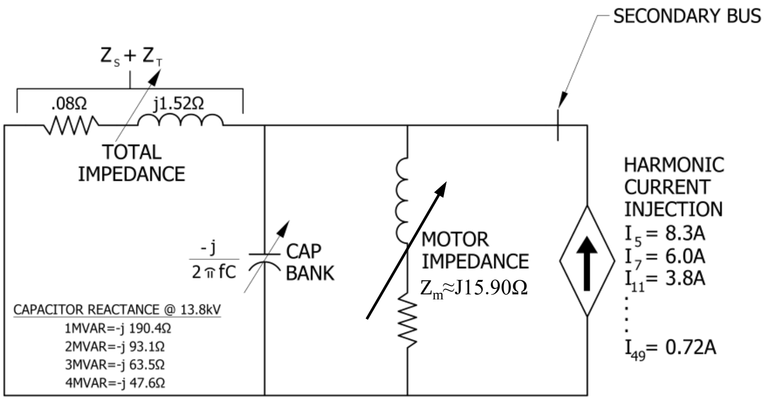
Impedance Scan Showing Resonance– 5 MVAR Capacitor Bank



$$n_{resonance} = \sqrt{\frac{X_C}{X_L}} = \sqrt{\frac{KVA_{SC}}{kvar_{cap\ bank}}} \approx \sqrt{\frac{47.6}{1.52}} \approx 5.59$$

- On simple systems (one capacitor and a purely inductive source impedance, the resonance can be estimated with formula shown on impedance scan.
- Peak of resonance is determined by resistance of network at resonance frequency.
- Resonance causes high voltage distortion and high current distortion in presence of harmonic current

Resonant Frequencies Can Shift For A Number Of Reasons

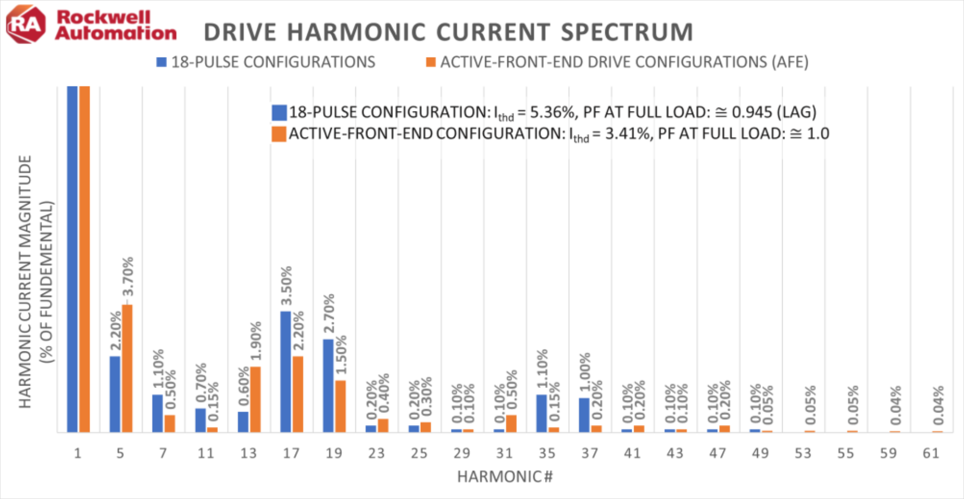


Always inspect impedance scans and consider what the impact would be for a in the impedance scans

Notes:

- Changes in short circuit impedance will result in shift of resonance. Changes include:
  - Transformer outage in a main-tie-main substation (significant change).
  - Utility source short circuit level
  - Motor load
  - Variation due to tap changer
- Consider all operating conditions
- Component tolerances
- Multi-stage capacitor banks
- Lower short circuit levels result in lower frequency resonance (where harmonic currents are typically higher).

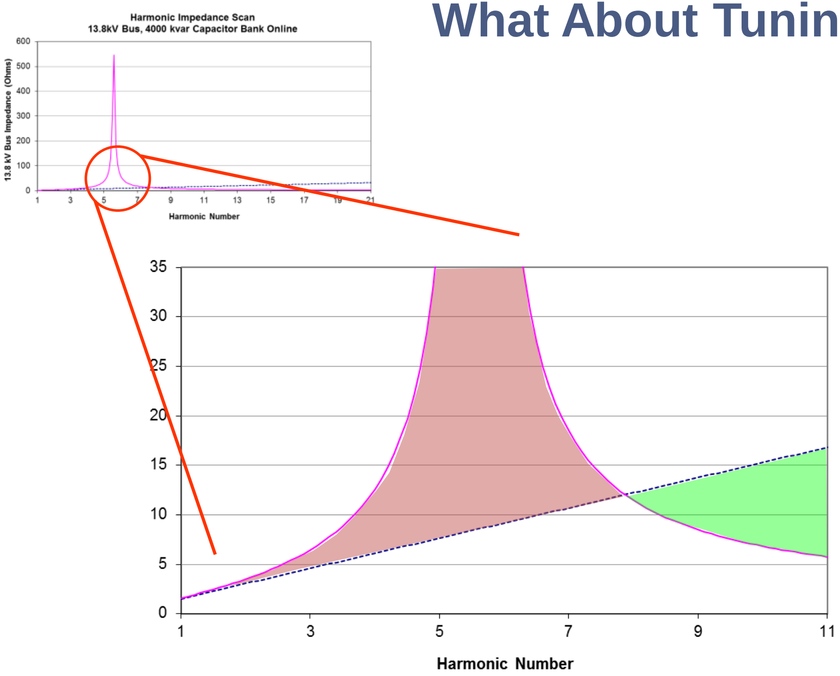
I Have AFE and High-Pulse Drive Configurations. It is IEEE 519 Compliant. Do I Need To Worry?



Key Points:

- Data supplied by: Rockwell Automation.
- **Answer: Yes.** Low level harmonic currents that correspond to resonant frequency will be amplified by the system resonance. In such cases the V_{thd} can easily surpass IEEE 519 recommended limits of 5%.
- For Example: A 5000 HP drive at 13.8kV has a fundamental current rating of near 156Amps. The 5^{th} harmonic current would equate to 0.022 x 156 amps = 3.43 amps for the 18-pulse drive and likewise 5.77 amps for the AFE drive.
- The previous slide showed the resonant impedance to be near 550 ohms for a slight shift in resonant point and as such the 18-pulse drive would result in V_{thd} near 52% and near 33% for the AFE Drive. **Yes, A problem.**

What About Tuning Around Resonance?



Notes:

- It is common for engineers to attempt to tune around resonance by changing the rating of the capacitor bank. This is not always possible without a significant change in the capacitor bank rating.
- For existing systems, voltage distortion typically increases when capacitors banks are installed.

Red: Increase in voltage distortion

Green: Decrease in voltage distortion

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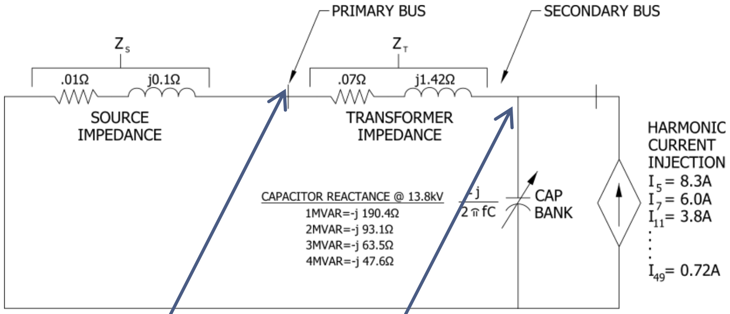
Parallel & Series Resonance (It Depends On Your Location)

- **Parallel Resonance**
  - Results in High impedance
- **Series Resonance**
  - Results in Low Impedance

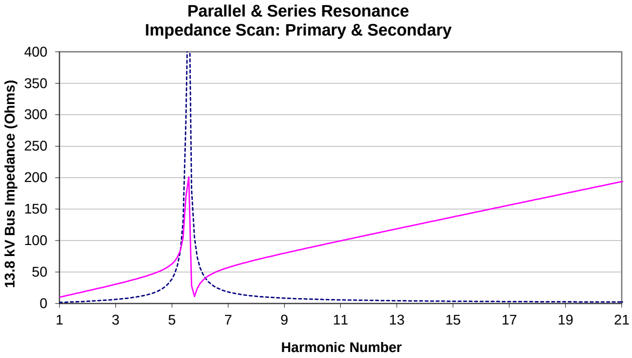


* Parallel Resonance

$$n_{parallel} \approx \sqrt{\frac{X_C}{X_S+X_T}}$$

** Series & Parallel Resonance

$$n_{parallel} \approx \sqrt{\frac{X_C}{X_S + X_T}} \qquad n_{Series} \approx \sqrt{\frac{X_C}{X_T}}$$



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Consider the Complexities Associated With Distributing Capacitors Through An Industrial Plant

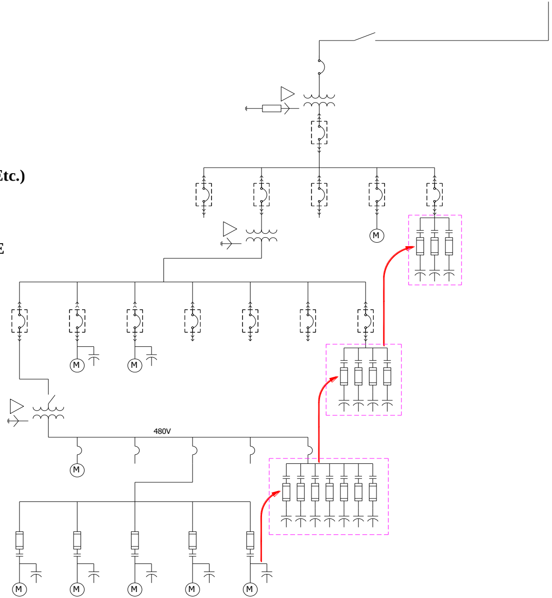
UTILITY SUPPLY VOLTAGE

MAIN SWITCHGEAR (13.8kV, 25kV, 34.5kV, Etc.)

MEDIUM VOLTAGE LOAD CENTER (4.16kV)

480 VOLT LOAD CENTER

480 VOLT MCC



Notes:

- Distributing capacitor banks throughout an industrial plant, especially at multiple voltage levels creates complex system impedance profiles can lead to problematic system.
- Series and parallel resonance exist between voltage levels.

NEPSI Recommends Power Factor Correction Be Done at Only One Voltage Level. Keep the System Simple.

Consider the Complexities Associated With Distributing Capacitors Through An Industrial Plant

Notes:

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NEPSI Recommends Power Factor Correction Be Done at Only One Voltage Level. Keep the System Simple.

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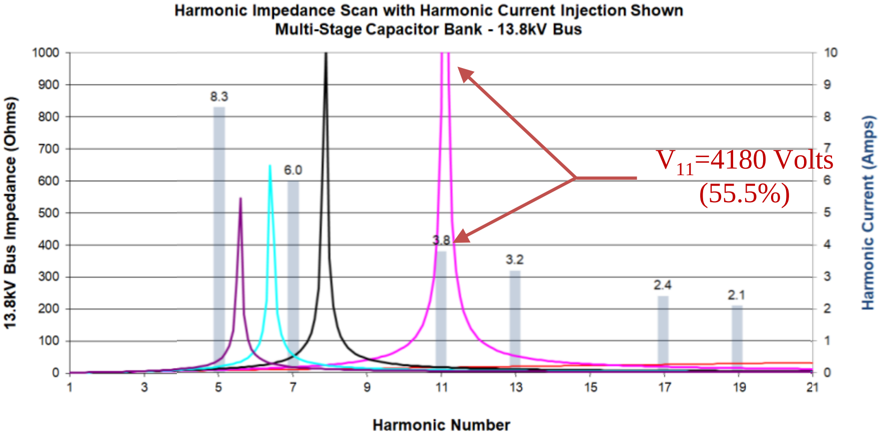
Multi-Stage Capacitor Banks



- Multi-stage capacitor banks result in different resonance points as bank stages come on.
- The resonant harmonic decreases as the capacitor bank stages up.
- Lower harmonic numbers are of more concern as harmonic current injection at these frequencies typically increase

1 MVAR → 11.19 Harmonic
2 MVAR → 7.82 Harmonic
3 MVAR → 6.46 Harmonic
4 MVAR → 5.59 Harmonic

Multi-Stage capacitor banks help to almost guarantee resonance issues

$$n_{resonance} = \sqrt{\frac{X_C}{X_L}} = \sqrt{\frac{KVA_{SC}}{kvar_{cap\ bank}}}$$

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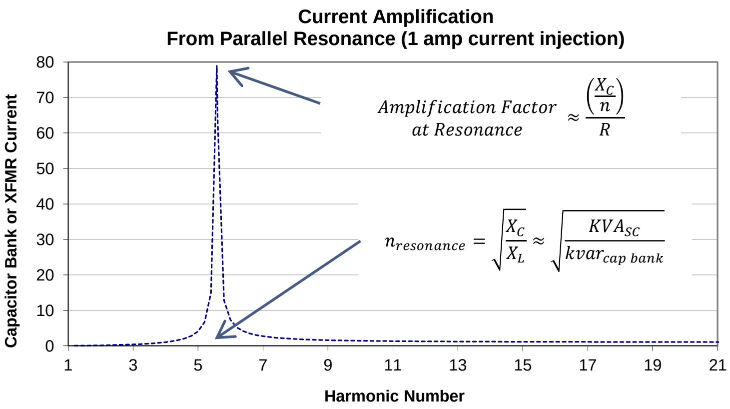
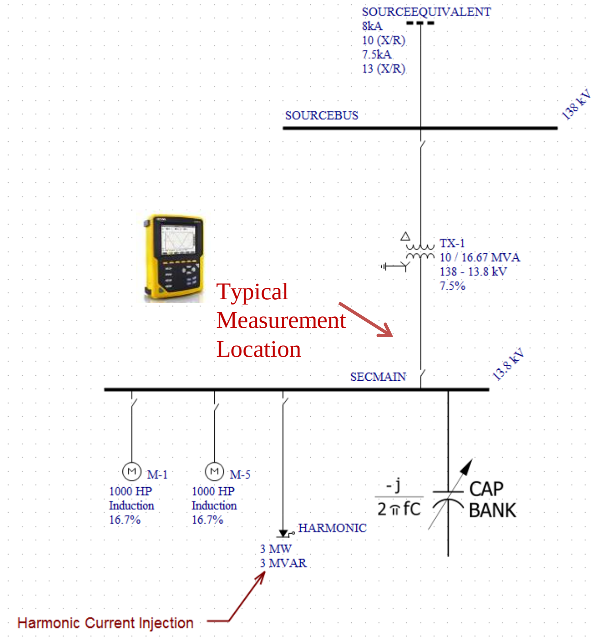
Current Amplification Slide (what happens during resonance)

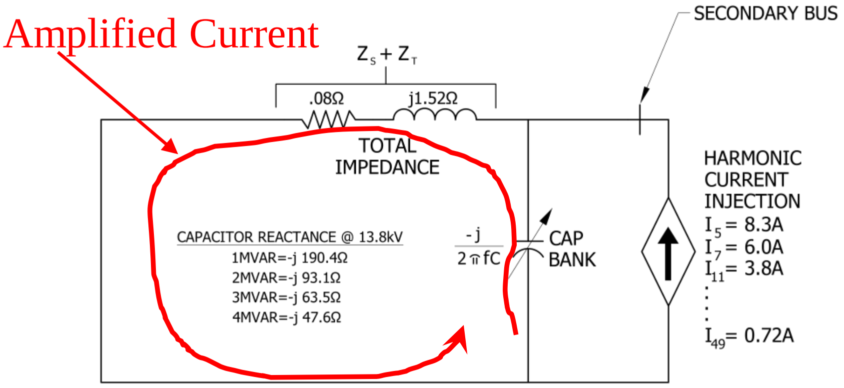


Notes:

- Parallel resonance causes current amplification.
- The addition of power factor correction capacitors will normally increase current distortion.
- Peak amplification occurs at the resonant frequency and is worst for systems with high X/R ratios.
- Since capacitor banks amplify harmonic currents, it is best to turn capacitor banks off to get a good measure of non-linear load harmonics.

Harmonic Measurements – Measure Right or Measure Again





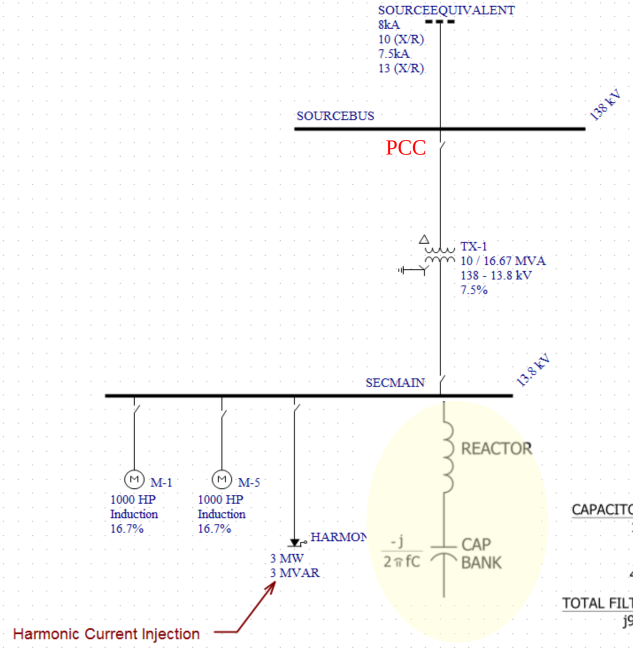
When taking harmonic measurements you must:

- Turn off all capacitor banks if measuring on transformer secondary

or

- Measure at the load. Measuring at the load might require measurement on multiple feeders.

What About Adding The Capacitor Bank As A Harmonic Filter Instead?



CAPACITOR REACTANCE (17.23kV RATED
1.49MVAR = -j199.47Ω

REACTOR REACTANCE
4.7th TUNING = j9.03Ω

TOTAL FILTER BRANCH REACTANCE @ 60Hz
j9.03 -j199.47 = -j190.4Ω

NEPSI Metal-Enclosed Harmonic Filter System Being Installed At Toquepala Mine Site in Peru

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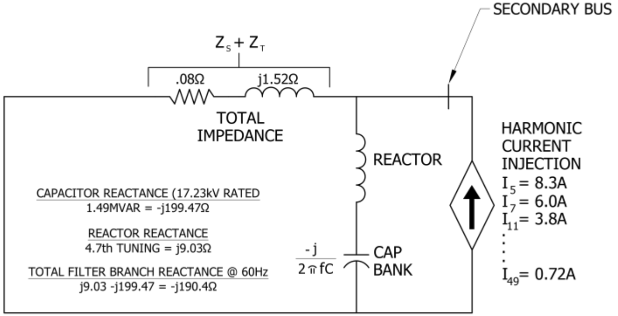
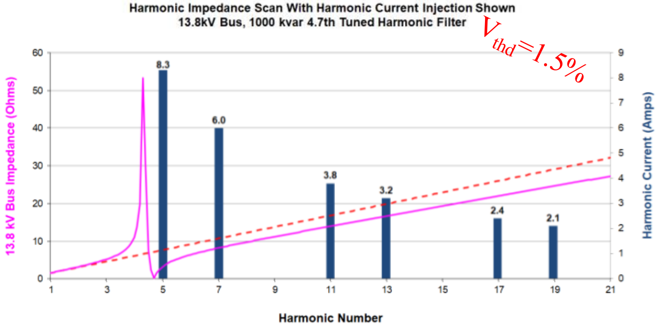
Equivalent Circuit With 4.7th Tuned Harmonic Filter Bank

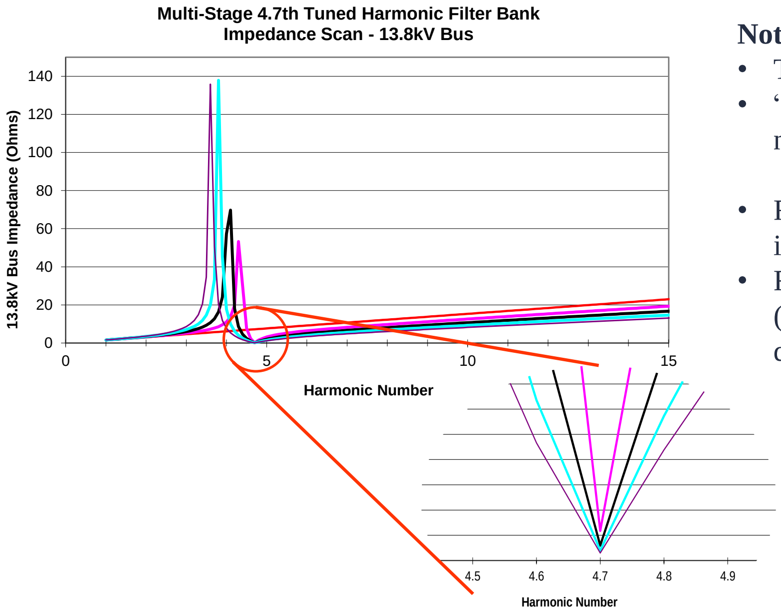




Notes:

- Reactor is chosen to tune capacitor to 4.7th harmonic.
- Same formula for tuning applies: $n_{tuning} = \sqrt{\frac{X_C}{X_L}}$.
- The filter offers low impedance path at its tuning point but also at other frequencies and thus reduces voltage distortion for all frequencies above its tuning point.
- The harmonic filter not only offers a low impedance path at its tuning frequency, it also precludes resonance at its tuning frequency and reduces current amplification at all harmonics above its tuning point.
- The filter tuning is not impacted by short circuit current level or other capacitors on the system.
- **Rule:** Filter tuning should always start at lowest significant harmonic. Normally the 5th harmonic.

Multi-Stage 4.7th Tuned Harmonic Filter

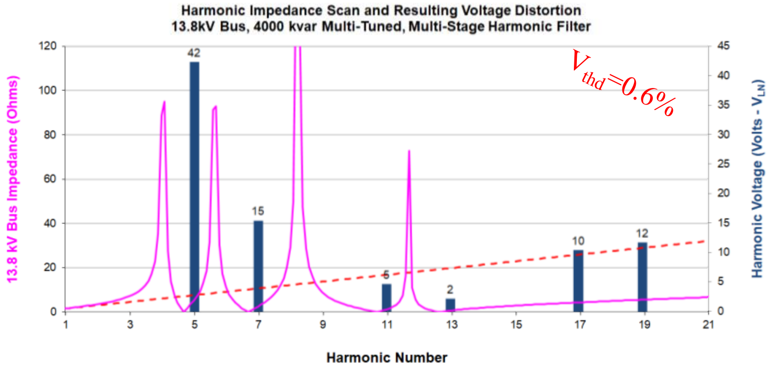


Notes:

- Tuning point does not change as stages are added
- "anti-resonance" point changes (decreases as the number of stages are added).
  - Consideration for 3rd harmonic
- Filtering capacity is added as the number of stages are increased
- Filter performance improves as stages are added (impedance at tuning point and adjacent harmonics decrease with increase number of stages).

1 MVAR → 11.19 Harmonic
2 MVAR → 7.82 Harmonic
3 MVAR → 6.46 Harmonic
4 MVAR → 5.59 Harmonic

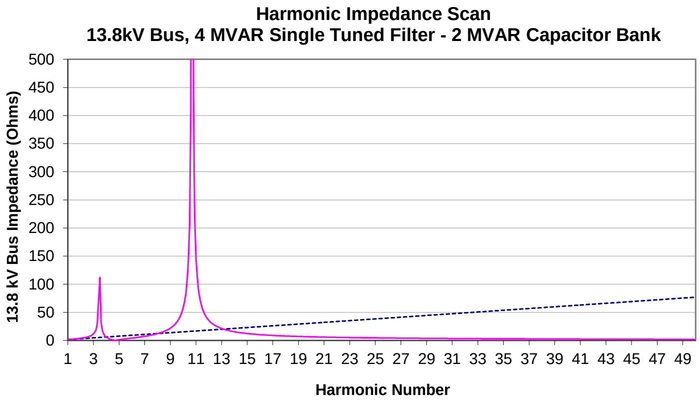
Multi-Stage & Multi-Tuned Harmonic Filter Banks
4.7th / 6.7th / 10.7th / 11.7th



Notes:

- Multi-Tuned Filter Banks are tuned to multiple frequencies
- They offer a low impedance path at each of their tuning points; providing better filtering when compared to single tuned filters.
- They preclude resonance at their tune frequencies
- Always check for resonance between stages
- Multi-tuned filters must be staged on in sequence due to resonance concerns. This reduces overall reliability of filter bank (i.e. if the 5th stage fails, or other stages must remain off).
- Not good in environments that have interharmonic or non-integer harmonics (i.e. cycloconverters, arc furnaces, etc.)

Effect of Stray Capacitance or other Capacitor Banks on Systems with Harmonic Filter



Notes:

- Stray capacitance and PFC capacitors create additional unwanted resonance(s) – especially with notch-tuned filter systems.
- Capacitance from cables should be considered
- PFC capacitor banks, being of higher capacitance can result in lower frequency resonance where harmonic current injection is higher.
- When stray capacitance is an issue, consider using C-HP and HP filter systems.

- For Harmonic Studies - be sure to account for stray cable capacitance

- **Do not apply capacitor banks and notch-tuned harmonic filter banks on the same bus!**

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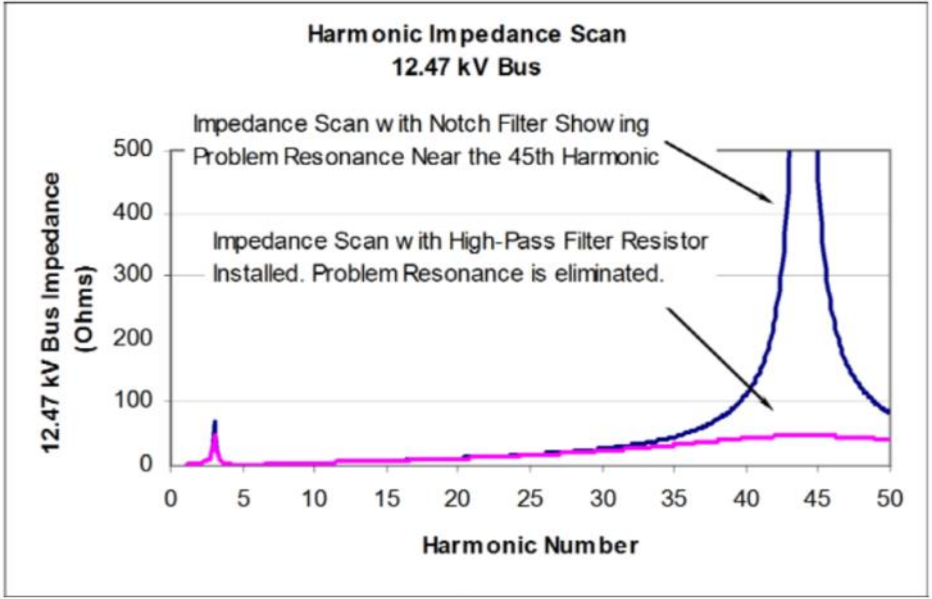
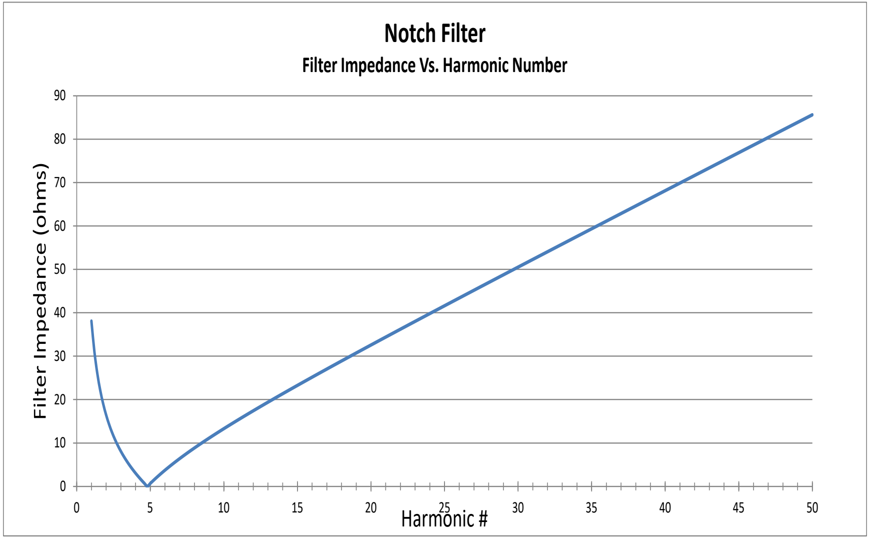
High-Pass Filters Dampen Harmonic Resonance



Notes:

- High-Pass filters resistors help to dampen resonance from stray cable capacitance and other remotely located power capacitor banks.
- High-pass filter types:
  - C-HP
  - HP

Notch Tuned Harmonic Filters



Notes:

- Low impedance at tuning point
- Low fundamental losses
- Less filtering at side-band harmonics
- More susceptible to inter-harmonic resonance and inter-filter harmonic resonance
- Lowest cost filter

Filter eady

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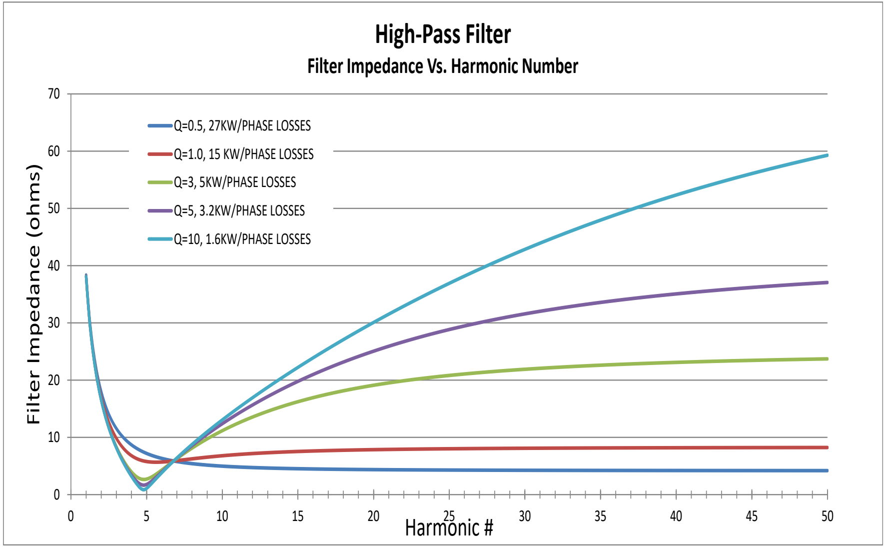
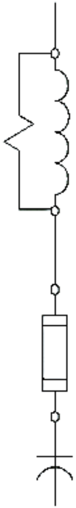
High-Pass Harmonic Filters

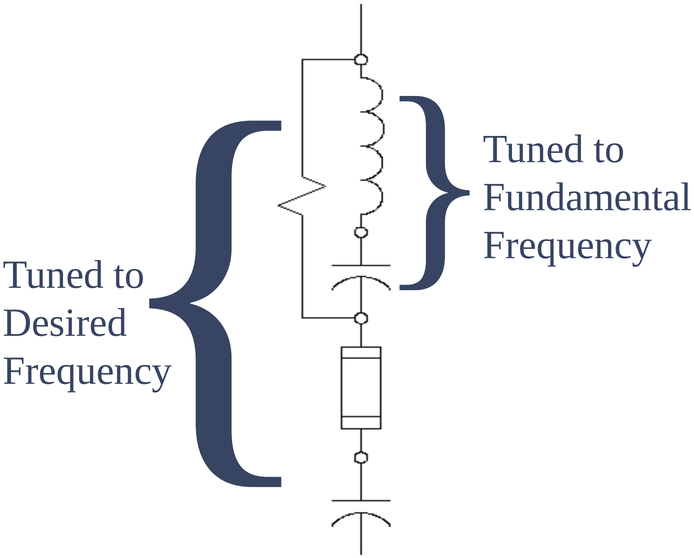




Notes:

- Attenuates higher order harmonics
- Dampens resonance
- Provides less filtering than notch filters at tuning point (as Q or R/X decreases)
- Has higher fundamental losses than notch filters
- Has higher cost when compared to Notch filters

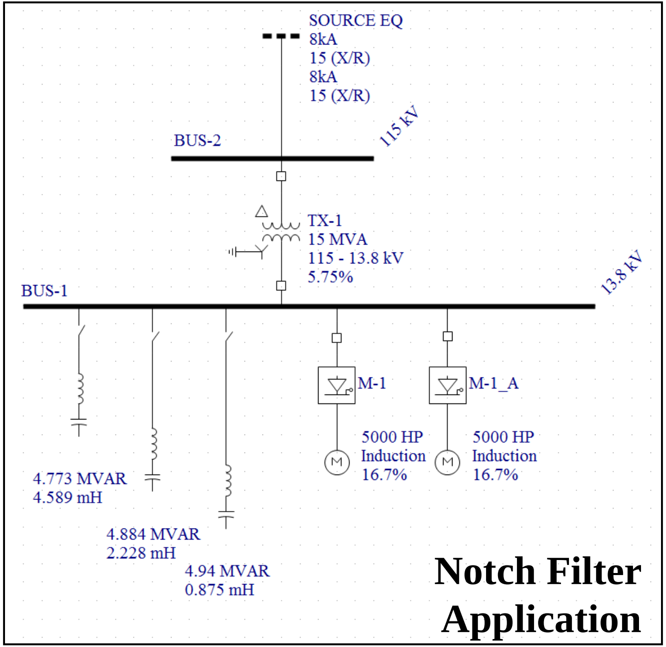
C-High-Pass Harmonic Filters

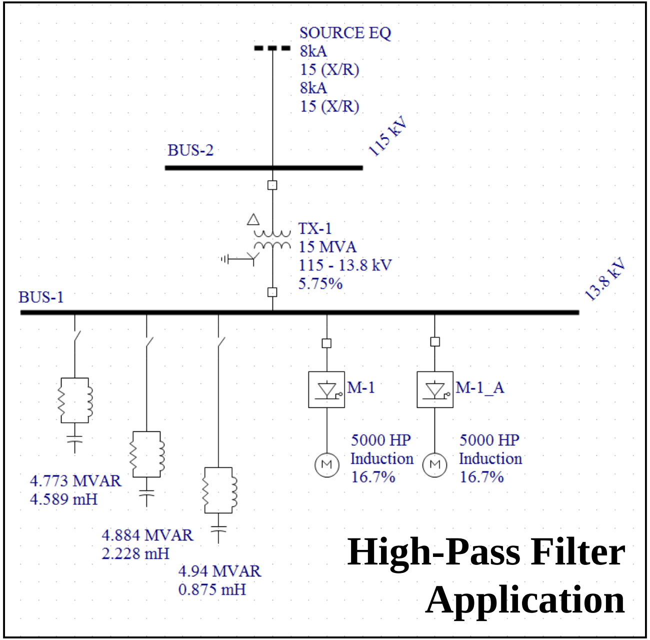


Notes:

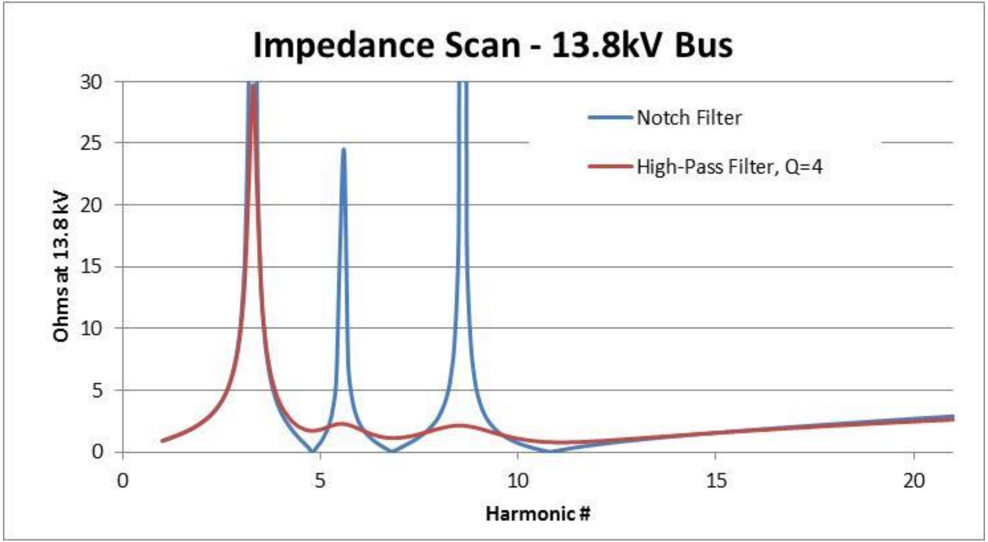
- Same benefits as standard high-pass-filter
- Impedance profile is nearly the same as standard high-pass filter
- Resistor has near 0 losses at fundamental frequency
- Higher dampening capability due to lower losses
- Harmonic losses are nearly the same as standard high-pass filters
- Higher Cost

High-Pass/Notch Filter Impedance Scan - Comparison





High-Pass/Notch Filter Impedance Scan – Comparison (continued)



Notes:

- High-Pass filters dampen resonant peaks between tuning points on multi-tuned harmonic filters
  - Important in cycloconverter applications or where interharmonics exist
- High-Pass filter tuning tolerance is less critical
- High-Pass filters help dampen unwanted resonance form remote capacitor banks or stray capacitance
- High-pass filters are better for attenuating higher frequencies harmonics

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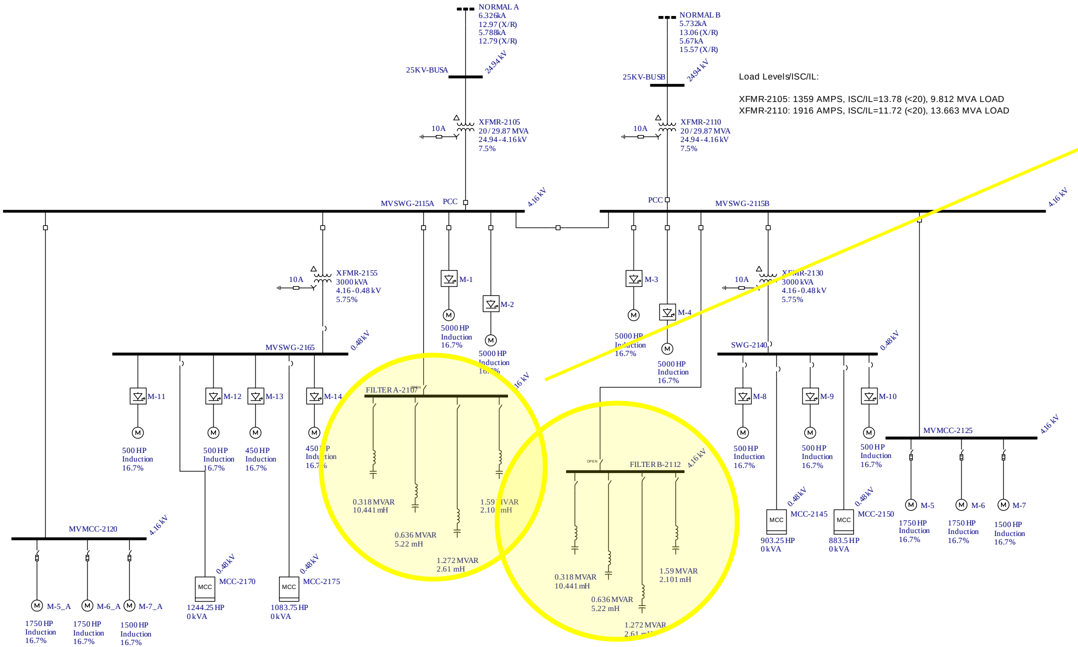
Detuned Versus Tuned Filter Banks – Gas Plant



Notes:

- Typical Gas Plant
- 6 MVAR of reactive power required per bus.
- Which should be used? Tuned or detuned filter banks?

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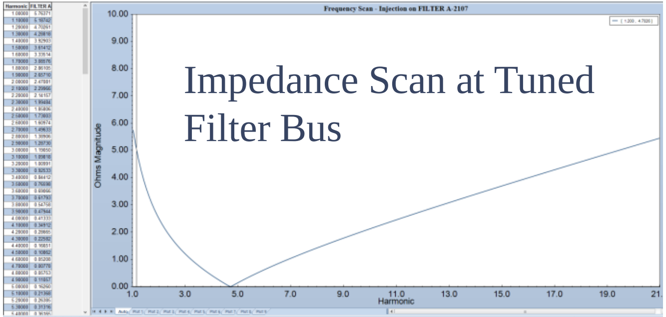
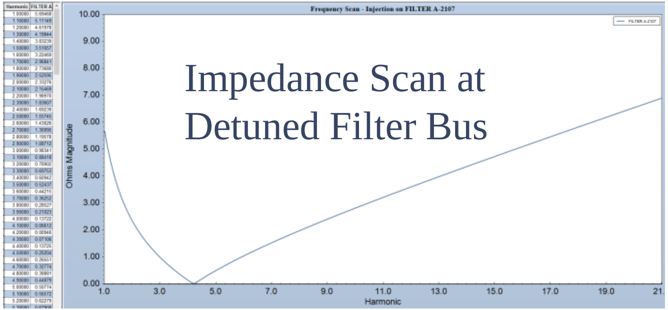
Detuned Versus Tuned Filter Banks





Notes:

- **Detuned filter banks** often refer to capacitor banks tuned to the 4.0 or 4.2 harmonic.
- **Tuned filter banks** often refer to capacitor banks tuned to the 4.8, 4.9 or 5.0 harmonic.
- The common belief is detuned filter banks block harmonics, are not susceptible to overload or overheating, prevent resonance, and are less expensive than tuned filter banks.

- Tuned Filter Impedance at 5.0 = 0.16 ohms
- Detuned Filter Impedance at 5.0 = 0.50775
- Source Impedance at 5.0 = 0.517

NEPSI Resources To Help With Filter Design And Harmonic Studies

- Website: www.nepsi.com
  - Filter design spreadsheet tools (indispensable tool) + others
  - Power System Calculators
  - Guide form specifications (by industry)
  - Common component cut sheets/instructions for MV filter banks and capacitor banks
  - NEPSI Product literature
  - Technical Notes
  - Case Studies
  - How-to-videos