Medium-Voltage Metal-Enclosed Products
Power Capacitor Banks, Harmonic Filter Banks, actiVAR™, & Surge Protection Products

Presentation On Harmonic Filter Design

Presented by Paul Steciuk
Medium voltage harmonic filters are used on all power systems at all voltage levels, but they are primarily used on industrial power systems at the medium-voltage level where large non-linear loads are in use, to improve power factor, prevent harmonic resonance, and mitigate harmonic distortion. Their design is not widely known or understood, and because of this, the task of design and specification is often left in the hands of the drive/rectifier supplier or electrification equipment packager. Because of this approach, due to margin stacking, the limited number of drive/rectifier suppliers, and the captive nature of the procurement process, the customer/EPC pays more and gets less. There is a better approach, and that is to break the filter package from the drive/rectifier supplier or electrification packager, create your own filter design and specification, and bid it out to vendors who specialize in harmonic filter design and manufacturing.

In this presentation, NEPSI demystifies harmonic filter design, paving the way for the EPC to break the filter package from the electrification packager and/or drive/rectifier supplier. NEPSI discusses the basics of filter design, filter topology, most prevalent filter types, their advantages/disadvantages, component selection and rating, vendor review, typical protection and control schemes, and more. This is an interactive and technical L&L where engineers can ask questions and receive answers from a NEPSI engineer who specializes in filter design, specification, and manufacturing.
Harmonic Filter Design – Presentation Outline

Corporate Introduction (5 Minutes)
- NEPSI’s Key Product offering
- Breaking the package

Filter Design Presentation
- Basics of Harmonic Filters, what they are, what they do
- Configuration Options
  - Metal-Enclosed
  - Open Air
  - E-House
- Key Filter Ratings (V, I, I_h, Q_{eff}, Tuning Point, etc.)
  - How is harmonic current rating is determined
- Filter Types, Topology of each, advantages/disadvantages of each
  - Notch
  - HP (Damping factor)
  - C-HP (Damping factor)
  - Single/Multi-stage
- Tuning calculation (calculating X_{eff}, L, C, R)
  - NEPSI Spreadsheet tool (a must have tool)
Filter Design Presentation (Continued)

- Component selection
  - Capacitor Rating Procedure, applicable standards
    - Heavy Duty Vs. Standard Duty (beware of claims), Specification, Vendor Review
  - Tuning Reactor Rating Procedure, applicable standards
    - Types: Air-Core | Iron-Core (Advantages/Disadvantages, Specification, Vendor Review)
    - Damping Resistor Rating Procedure, applicable standards, types, # of series elements, specification, vendor review
- Switching Device (Breaker/Switches)
- Typical Protection
  - Capacitor protection (internally fused vs. externally fused)
    - Blown Fuse Detection
  - Reactor Protection
    - Overload protection / thermal protection
  - Resistor Protection
  - Short Circuit Protection (50/51 phase/ground), arc flash
    - Over-voltage, $V_{thd}/I_{thd}$, Over-Temperature, Fan failure
- Typical Control

NEPSI Resources

Questions/Answers
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

**Red Chris Mine - British Columbia**

*23 MVAR, 24.9 kV, 5-Stage, All-Inclusive Harmonic Filter System*
Large Harmonic Filter One-Line Diagram

Large Harmonic Filter System 2 of 2

This presentation contains confidential and privileged information for the sole use of the intended recipient. Distribution, disclosure to other third parties is prohibited without prior consent.
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
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.
Technical Presentation
Harmonic Filter Design

Presented by Paul Steciuk
Paul.Steciuk@NEPSI.COM
Harmonic Filters – What Are They and What Do They Do?

What They Do -

• **Correct Power Factor** (Reactive Compensation)
  • Usually to avoid power factor penalties or comply with interconnect agreement
• **Reduce Harmonic Current / Voltage Distortion**
  • By providing a low impedance path for harmonic currents
  • To Become compliant with harmonic standards
    • IEEE 519
    • IEC 61000-3-2 (EN 61000-3-2)
    • Many others
• **Prevent Harmonic Resonance**
  • Harmonic filters installed for the prevention of resonance are often called “**de-tuned**” **capacitor banks**.
    • Applied when high-pulse drives are used.

What They Are -

• **Most Simply Stated** –
  • A capacitor bank with a tuning reactor
  • The inductive reactance is a fraction of the capacitive reactance of the capacitor bank.
  As a result, they are, in many ways, a capacitor bank.
Harmonic Filter Configuration Options

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.

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.
Key Filter Ratings

- **Reactive Power Rating (KVAR / MVAR, 3-Phase Value)**
  - Usually based on reactive power requirement of load
  - May be determined by harmonic duty requirements

- **Voltage**, based on system voltage (KV_{LL})

- **Insulation Level (KV)**
  - BIL / 1 Minute Withstand
  - Based on standard rating for voltage class of equipment +pollution level, + elevation, + consideration for increased reliability and arc flash mitigation

- **Tuning Point** (Hertz or Harmonic Number, i.e. 282 Hertz or 4.7th Harmonic for 60 Hertz System)

- **Filter Type** (Notch, C-HP, HP)
  - For C-HP, HP
    - Damping Factor (R/X\_inductor at tuning frequency)
    - Resistor Rating (Ohms, KW)

- **Fundamental Current Rating**, I\_1, (Amps), at 10% Over-voltage

- **Harmonic Current Ratings** (Amps), Include all significant harmonics Under worst case conditions
  - I\_5, I\_7, I\_11, I\_13,... etc. (be very conservative)
How Are Harmonic Filter Ratings Determined?

Filter Ratings

- Power System Studies
  - Load Flow Analysis
    - Determines reactive power rating of filter (MVAR)
- Harmonic Analysis
  - Determines filter tuning
  - Determines expected harmonic current flow into filter branch(s)
  - Filter type (Notch, C-HP, HP)
- Based on above studies, L, R, C Filter Parameters, and reactive power ratings are determined. The equipment specification is not normally developed from the study.

Filter Component Ratings (Capacitors | Reactors | Resistors)

- Harmonic Analysis Programs
- Spreadsheet Tools (NEPSI offers such a tool at: http://nepsi.com/resources/spreadsheet-tools/)
Harmonic Filter – Basic Concepts

Harmonic Impedance Scan
Filter Bus (No Source Impedance) / Main Bus (No Filter)

Filter Impedance
Source Impedance

Harmonic Current Injection
4 MVAR 4 Stage/4 Step Capacitor Bank
4 Stages of 1 MVAR
Harmonic Filter – Basic Concepts

Harmonic Impedance Scan
13.8kV Bus, 1000 kvar 4.7th Tuned Harmonic Filter

Harmonic Current Injection
4 MVAR 4 Stage/4 Step Capacitor Bank
4 Stages of 1 MVAR

SOURCEEQUIVALENT
8kA
10 (X/R)

CAPBANK
1.491 MVAR
23.953 mH

SECMAIN
M-1
1000 HP
Induction
16.7%

M-5
1000 HP
Induction
16.7%

PCC
13.8 kV
7.5%

CAPBUS
1.491 MVAR
23.953 mH

SOURCEBUS
PCC
13.8 kV

138 kV
SECMAIN
13.8 kV
M-1
1000 HP
Induction
16.7%

M-5
1000 HP
Induction
16.7%

Harmonic Number

1 3 5 7 9 11 13 15 17 19 21

1.52Ω
.08Ω

Zs + Zf

TOTAL IMPEDANCE

HARMONIC CURRENT INJECTION

I2 = 8.3A
I7 = 6.0A
I11 = 3.8A

I49 = 0.72A
### Most Common Filter Types Used at Medium Voltage Level

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notch</td>
<td>Preferred due to low cost, low losses, and simplicity</td>
</tr>
<tr>
<td>HP and C-HP</td>
<td>Common in projects where non-characteristic harmonics might be present, on systems with large drives, and where there is stray capacitance concerns</td>
</tr>
</tbody>
</table>

- **Notch Filters** are preferred due to low cost, low losses, and simplicity
  - Most common on industrial power systems
- **HP and C-HP** Filters are common in projects where non-characteristic harmonics might be present, on systems with large drives, and where there is stray capacitance concerns
  - Most common in mine applications and where large drive applications (LCI / Cycloconverter)
  - Projects with significant amounts of cable capacitance (wind farms)
- Filter types, tuning point, reactive power rating, and quantity can be grouped together to create multi-staged harmonic filter systems

---

**Application Considerations**

- **Increasing Cost / Complexity $$$$$**
Notch Tuned Filter

Key Characteristics

- Low impedance at tuning point
- Low fundamental losses
- Less filtering at side-band harmonics
- More susceptible to inter-harmonic resonance
- Lowest cost filter
High-Pass (HP) Tuned Filter (Damped Harmonic Filter)

Key Characteristics

- Attenuates higher order harmonics
- Dampens resonance
- Provides less filtering than notch filters at tuning point (as Q or Damping Factor (R/X) decreases)
- Has higher fundamental losses than notch filters
- Has higher cost when compared to Notch filters
- Commonly used in large drive projects and where inter-harmonic resonance is of concern.
C-High-Pass (C-HP) Tuned Filter (Damped Harmonic Filter)

Key Characteristics

- Same benefits as standard high-pass-filter
- Impedance profile is 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 than C-HP and Notch Filters
- Commonly used in large drive projects and where inter-harmonic resonance is of concern.
- Most often applied only at tuned frequencies below the 5th harmonic (i.e. 2nd, 3rd, 4th, harmonics)
High-Pass Vs. Notch Filter Impedance Scan Comparison

Notch Filter Application

High-Pass Filter Application

This presentation contains confidential and privileged information for the sole use of the intended recipient. Distribution, disclosure to other third parties is prohibited without prior consent.
High-Pass filters dampen resonant peaks between tuning points on multi-tuned harmonic filters
- Important in cycloconverter and large drive 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

Impedance Scan - 13.8kV Bus

- High-Pass filters dampen resonant peaks between tuning points on multi-tuned harmonic filters
- Important in cycloconverter and large drive 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

This presentation contains confidential and privileged information for the sole use of the intended recipient. Distribution, disclosure to other third parties is prohibited without prior consent.
High-Pass Filters (C-HP & HP) Dampen Resonance Conditions

High-Pass filters also help to dampen resonance from stray cable capacitance and other remotely located power capacitor banks.
### Tuning Calculation ($X_L$, $X_C$, $L$, $C$) – Notch Filter Design

(13.8kV, 1000 kvar, 4.7th Tuned Notch Filter Type)

- **$Q_{eff}$**: Output MVAR Rating of Filter
  \[
  Q_{eff} = \frac{\text{Desired 3 Phase kvar}}{1000} = 1.0 \text{ MVAR}
  \]

- **$kV_{LLSYS}$**: Filter Nominal Line – to – Line Voltage Rating (KV) = 13.8 kV

\[
X_{eff} = \frac{kV_{LLSYS}^2}{Q_{eff}} \text{ (ohms)} = \frac{13.8^2}{1.0} = 190.4 \text{ (ohms)}
\]

\[
X_C = \left(\frac{h^2}{h^2-1}\right) X_{eff} \text{ (ohms)} = \left(\frac{4.7^2}{4.7^2-1}\right) 190.4 \text{ (ohms)} = 199.47 \text{ (ohms)}
\]

\[
X_L = \frac{X_C}{h^2} = \frac{199.47}{4.7^2} = 9.03 \text{ ohms}
\]

\[
H \text{ (inductance)} = \frac{X_L}{2\pi f} \times 1000(\text{mH}) = \frac{9.03}{2\pi \times 60} \times 1000(\text{mH}) = 23.95 \text{ mH}
\]

\[
Q_{\text{RATED PER PHASE (MVAR)}} = \left(\frac{V_{\text{CAP RATING}}}{X_C}\right)^2 = \left(\frac{9.54}{199.47}\right)^2 = 0.456 \text{ MVAR/Phase}
\]

\[
I_{\text{RATED FUNDAMENTAL}} = \frac{Q_{eff}}{1.73 \times kV_{LLSYS}} \times 1000 = \frac{1.0}{1.73 \times 13.8} \times 1000 = 41.88 \text{ amps}
\]

\[
I_{\text{FILTER RMS CURRENT}} = \sqrt{\sum_{n=1}^{n} I_n^2}
\]

$h$ = Tuning Point

$X_C$ = Capacitive Reactance of Capacitor (ohms)

$X_L$ = Inductive Reactance of Reactor (ohms)

$f$ = Filter System Fundamental Frequency (Hz)

$$
C = \frac{1}{2\pi f X_C} \quad L = \frac{X_L}{2\pi f}
$$

$I_n$ = Current in Amps at Each Harmonic

This presentation contains confidential and privileged information for the sole use of the intended recipient. Distribution, disclosure to other third parties is prohibited without prior consent.
The image contains a Tuning Calculation formula for a High Pass (HP) Filter Design. The formulas include:

- Output MVAR Rating of Filter: $Q_{eff} = \frac{\text{Desired 3 Phase kvar}}{1000} = 1.0$ MVAR
- Filter Nominal Line-to-Line Voltage Rating (KV): $kV_{L_{SYS}} = 13.8$ kV
- Capacitive Reactance of Capacitor (Ohms): $X_c = \frac{kV_{L_{SYS}}^2}{Q_{eff}} = 190.4$ Ohms
- Inductive Reactance of Reactor (Ohms): $X_L = \left(\frac{h^2}{h^2-1}\right) X_{eff} = \left(\frac{4.7^2}{4.7^2-1}\right) 190.4$ Ohms = 199.4 Ohms
- Inductive Reactance of Reactor (Ohms) at Tuning Point: $X_L = \frac{X_c}{h^2} = \frac{199.4}{4.7^2} = 9.03$ Ohms
- Inductance at Tuning Point: $H = \frac{X_L}{2\pi f} \times 1000(mH) = \frac{9.03}{2\pi \times 60} \times 1000(mH) = 23.95$ mH
- MVAR per Phase: $Q_{\text{RATED PER PHASE (MVAR)}} = \frac{(V_{\text{CAP RATING}})^2}{X_c} = \frac{(9.54)^2}{199.47} = 0.456$ MVAR/Phase
- Rated Fundamental Current: $I_{\text{RATED FUNDAMENTAL}} = \frac{Q_{eff}}{1.73 \times kV_{L_{SYS}}} \times 1000 = \frac{1.0}{1.73 \times 13.8} \times 1000 = 41.88$ amps
- RMS Current: $I_{\text{FILTER RMS CURRENT}} = \sqrt{\sum_{n=1}^{\infty} I_n^2}$
Tuning Calculation ($X_L$, $X_C$, L, C, R) – C-HP Filter Design

(13.8kV, 1000 kvar, 4.7th Tuned C-HP Filter Type)

$$Q_{eff} = \text{Output MVAR Rating of Filter} = \frac{\text{Desired 3 Phase kvar}}{1000} = 1.0 \, \text{MVAR}$$

$$kV_{LLSYS} = \text{Filter Nominal Line – to – Line Voltage Rating (KV)} = 13.8 \, \text{kV}$$

$$X_{eff} = \frac{kV_{LLSYS}^2}{Q_{eff}} \, \text{(ohms)} = X_{CM} = \frac{13.8^2}{1.0} = 190.4 \, \text{(ohms)}$$

$$X_L = \frac{X_{eff}}{h^2-1} = \frac{190.4}{4.7^2-1} = 9.03 \, \text{ohms}$$

$$X_{CA} = X_L = 9.03 \, \text{ohms}$$

$$H\text{(inductance)} = \frac{X_L}{2\pi f} \times 1000(mH) = \frac{9.03}{2\pi \times 60} \times 1000(mH) = 23.95 \, \text{mH}$$

$$Q_{CA \, RATED \, PER \, PHASE \, (MVAR)} = \frac{(V_{CAP \, RATING})^2}{X_{CA}} = \frac{(0.6)^2}{9.03} = 0.040 \, \text{MVAR/Phase}$$

$$Q_{CM \, RATED \, PER \, PHASE \, (MVAR)} = \frac{(V_{CAP \, RATING})^2}{X_{CM}} = \frac{(9.54)^2}{190.4} = 0.478 \, \text{kvar/Phase}$$

$$I_{RATED \, FUNDAMENTAL} = \frac{Q_{eff}}{1.73 \times kV_{LLSYS}} \times 1000 = \frac{1.0}{1.73 \times 13.8} \times 1000 = 41.88 \, \text{amps}$$

$$I_{FILTER \, RMS \, CURRENT} = \sqrt{\sum_{n=1}^{n} I_n^2}$$

$I_n$ = Current in Amps at Each Harmonic

This presentation contains confidential and privileged information for the sole use of the intended recipient. Distribution, disclosure to other third parties is prohibited without prior consent.
How filters are really designed:

- Spreadsheet tools are most often used to confirm ratings and do design work.
  - Required values: System voltage, reactive power rating, tuning point, system frequency, expected harmonic current duty (don’t forget to add margin)
  - Harmonic analysis programs calculate expected performance (IEEE 519 compliance, Vthd, Ithd, etc.).
  - Expected harmonic current flow into filter is used as input to spreadsheet tools for validating component duty rating against standards.
  - Spreadsheet tool provides calculation for all major filter types: Notch, High Pass (HP), and C-High-Pass (C-HP)
Component Selection & Rating - Capacitors, Reactors, Resistors

Recommendations When Selecting and Rating Components

• Be conservative
  • Systems Change / Expand
  • Calculations Don’t Always Match Reality
    • Wrong Assumptions
    • Wrong Input Data
  • Cost Increase For A Conservative Design Is Minimal – Pennies on the dollar
  • Component Supplier Ratings Don’t Always Meet Expectations
  • Improved Reliability
• Use Only Reputable Manufacturers
  • Consider Availability, Service, and How Supplier Behaves When There Are Problems

The cost for higher-rated, higher-quality components are pennies on the dollar

Improve reliability, ensure success over-specify
Shunt Power Capacitors

Capacitor Standards
- C22.2 No. 190-M1985, *Capacitors for Power Factor Correction*
- IEC 60871-1, *Shunt Capacitors for a.c. Power Systems Having a Rated Voltage Above 1000V*

Application Standards –
- IEEE Std. 1531 – *IEEE Guide for Application and Specification of Harmonic Filters*

Main Suppliers:
ABB, Cooper Power (Eaton), General Electric (GE), Vishay

Type:
Internally Fuses | Externally Fused

Most Prevalent Connection:
Ungrounded-Wye or Split-Wye-Ungrounded

2-Bushing, Single-Phase Capacitors
Shunt Power Capacitors – Selection of Ratings

Choose a capacitor voltage rating, calculate its maximum RMS current and voltage ratings, kvar rating, and peak voltage rating and compare it to the expected duty it will see when in operation as part of the harmonic filter.

Capacitor Standard Maximum Ratings

• 110% of rated RMS voltage

• 120% of rated peak voltage, i.e. peak voltage not exceeding 1.2 x (square root of two or 1.414) x rated rms voltage, including harmonics, but excluding transients

• 135% of nominal RMS current based on rated kvar and rated voltage

• 135% of rated kvar

X_c = Fundamental Capacitive Reactance of Capacitor

\[ V_{CAP \ harmonics \ voltage} (n) = \frac{X_c}{n} \times I_{filter} (n) \]

Capacitor Duty Rating in Filter

\[ V_{CAP \ rms \ voltage} = \sqrt{\sum_{n=1}^{n} V_{CAP \ harmonics \ voltage} (n)^2} \]

\[ V_{CAP \ peak \ voltage} = 1.414 \times \sum_{n=1}^{n} V_{CAP \ harmonics \ voltage} (n) \]

\[ I_{CAP \ rms \ current} = \sqrt{\sum_{n=1}^{n} I_{filter}^2 (n)} \]

\[ Q_{CAPACITOR} = \sum_{n=1}^{n} \frac{X_c}{n} \times I_{filter}^2 (n) / 1000 \]

The minimum capacitor voltage rating for ungrounded-wye connected capacitor banks is the system’s line-to-neutral voltage. For lower tuned filters, the voltage must be higher. The tuning reactor adds fundamental voltage to the capacitor and this value must be accounted for. A typical starting point would be 1.25 x V_{LN}
Capacitors May Be Advertised As Exceeding Industry Standards

<table>
<thead>
<tr>
<th>Continuous RMS Overvoltage</th>
<th>Standard-Duty (SD)</th>
<th>Heavy-Duty (HD)</th>
<th>Extreme-Duty (XD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110% of rated voltage</td>
<td>125% of rated voltage</td>
<td>125% of rated voltage</td>
<td></td>
</tr>
<tr>
<td>Peak Overvoltage</td>
<td>120% of rated RMS voltage</td>
<td>135% of rated RMS voltage</td>
<td>135% of rated RMS voltage</td>
</tr>
<tr>
<td>Maximum Fault Current Handling</td>
<td>10,000 A</td>
<td>10,000 A</td>
<td>15,000 A</td>
</tr>
<tr>
<td>Ambient Operating Temperature</td>
<td>-40 °C to +55 °C</td>
<td>-40 °C to +55 °C</td>
<td>-50 °C to +55 °C</td>
</tr>
<tr>
<td>Performance Test Per IEEE Std. 18-2012</td>
<td>N/A</td>
<td>Meet @ -40 °C</td>
<td>Meet @ -50 °C</td>
</tr>
<tr>
<td>BIL Ratings</td>
<td>95, 125, 150, and 200 kV BIL</td>
<td>95, 125, 150, and 200 kV BIL</td>
<td>95, 125, 150, and 200 kV BIL</td>
</tr>
<tr>
<td>Applications</td>
<td>Typical utility transmission and distribution application</td>
<td>Electric power systems where high reliable reactive power is needed</td>
<td>Industrial power systems, harmonic filter applications</td>
</tr>
<tr>
<td>Ratings</td>
<td>50 to 600 kvar</td>
<td>50 to 600 kvar</td>
<td>50 to 600 kvar</td>
</tr>
<tr>
<td>Voltage Ratings</td>
<td>2400 to 22800 V</td>
<td>2400 to 22800 V</td>
<td>2400 to 22800 V</td>
</tr>
<tr>
<td>Routine Tests</td>
<td>Standard</td>
<td>Standard</td>
<td>Special</td>
</tr>
</tbody>
</table>

Application Note

- Capacitors may be purchased with additional margin beyond their nameplate rating.
- Cold temperature ratings should always be used in Canada and must be CSA rated.
- Capacitors used in harmonic filters should leave 10% RMS overvoltage and 20% peak overvoltage capability for system overvoltage.
- Standard allows for 0 +10% on capacitance. They are typically 0 to +3%.

Know what capacitor you are getting, consider standard duty rating only as test per standards are based on nameplate values and not extra-duty rating.

Table from Cooper Power, ABB, GE, and others have a similar table, but additional margins can vary
Considerations…

- Shunt Power Capacitor suppliers build **custom sizes** with no cost premium.
- NEPSI typically uses standard voltage ratings, but not always and it is not necessary.
- Tables only go up to 22,800 volts, but suppliers will go as high as 24,000 volts.
- **Internally fuse capacitors stop at 12kV** and as a result require multiple series capacitors to obtain line-to-neutral voltage on higher-voltage systems, 20kV and up.

---

**Table 2. Ratings and Catalog Numbers for 60 Hz Standard-Duty Single- and Double-Bushing Capacitors (continued)**

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>BIL (kV)</th>
<th>300 kvar Capacitors</th>
<th>400 kvar Capacitors</th>
<th>500 kvar Capacitors</th>
<th>600 kvar Capacitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>2400</td>
<td>95</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2770</td>
<td>95</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>4600</td>
<td>95</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>4800</td>
<td>95</td>
<td>CEP13M4</td>
<td>CEP13M4</td>
<td>CEP13M4</td>
<td>CEP13M4</td>
</tr>
<tr>
<td>6640</td>
<td>95</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
</tr>
<tr>
<td>7200</td>
<td>95</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
</tr>
<tr>
<td>7560</td>
<td>95</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
</tr>
<tr>
<td>7800</td>
<td>95</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
</tr>
<tr>
<td>8320</td>
<td>95</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
</tr>
<tr>
<td>8960</td>
<td>95</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
<td>CEP13M56</td>
</tr>
<tr>
<td>11400</td>
<td>125</td>
<td>CEP13M6</td>
<td>CEP13M6</td>
<td>CEP13M6</td>
<td>CEP13M6</td>
</tr>
<tr>
<td>12370</td>
<td>125</td>
<td>CEP13M6</td>
<td>CEP13M6</td>
<td>CEP13M6</td>
<td>CEP13M6</td>
</tr>
<tr>
<td>13800</td>
<td>125</td>
<td>CEP13M6</td>
<td>CEP13M6</td>
<td>CEP13M6</td>
<td>CEP13M6</td>
</tr>
<tr>
<td>14400</td>
<td>125</td>
<td>CEP13M6</td>
<td>CEP13M6</td>
<td>CEP13M6</td>
<td>CEP13M6</td>
</tr>
</tbody>
</table>

---

**Table 1. Bushing Characteristics and Weights**

<table>
<thead>
<tr>
<th>BIL (kV)</th>
<th>Creepage Distance (in.)</th>
<th>Strike Distance (in.)</th>
<th>60-sec. Dry (kV)</th>
<th>10-sec. Wet (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>12.00</td>
<td>6.25</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>150**</td>
<td>22.00</td>
<td>9.50</td>
<td>90</td>
<td>50</td>
</tr>
<tr>
<td>200</td>
<td>32.00</td>
<td>14.00</td>
<td>80</td>
<td>75</td>
</tr>
</tbody>
</table>

---

* Bushings furnished on standard capacitors shown in Tables 2, 3, and 4. The bushings used in 95 kV BIL rated capacitors are also capable of meeting 110 kV BIL and are used in 110 kV BIL rated capacitors.

** The bushings used in 150 kV BIL rated capacitors are also used in 125 kV BIL rated capacitor designs.

---

This presentation contains confidential and privileged information for the sole use of the intended recipient. Distribution, disclosure to other third parties is prohibited without prior consent.
Standards require 5-minute discharge device (resistor)
- Discharge from peak voltage to 50 volts in 300 seconds or less
- Faster discharge times can be purchased ~ 180 seconds
- Transformers may be used to discharge trapped charge to allow for faster re-energization

\[ \text{Capacitor Voltage} = 1.05e^{-0.05 \times \text{Time}} \]

1 Per Unit Voltage = 1.414 x Rated RMS Voltage of Capacitor
Typical Capacitor Construction

Typical Construction

- Capacitors are built of series and parallel sections to obtain desired kvar and voltage rating.
- Sections typically have a 2000 volt rating.
- 1-Bushing and 2-Bushing designs
- Are filled with a non-PCB dielectric fluid, about 5 Gallons (18.9 Liters) per capacitor
- Typically weigh less than 120 Pounds (~54 Kilograms)

Application Note:

- Capacitor section failures account for nearly 95% of capacitor failures
- A capacitor section failure will result in an increase of capacitance and additional stress on all remaining sections
- Discharge resistors seldom fail

\[
\text{Capacitance Increase} = \frac{\text{(\# of Series Sections)}}{\text{(# of series section failures) – (# of failed sections)}}
\]
Typical Capacitor Weight

- 667 kvar, 24.94kV
- 647 kvar, 24.94kV
- 600 kvar, 22.2kV
- 592 kvar, 21kV
- 525 kvar, 19.94kV
- 500 kvar, 22.8kV
- 453 kvar, 14.4kV

Weight (LBS)
Modern All-Film Power Capacitors Are Quite Reliable

ABB Capacitors - Quebec City

<table>
<thead>
<tr>
<th>ABB CAPACITORS FIELD FAILURE RATE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Year of MFG</strong></td>
</tr>
<tr>
<td><strong>Quebec average</strong></td>
</tr>
<tr>
<td>2002-2008</td>
</tr>
<tr>
<td><strong>China</strong></td>
</tr>
<tr>
<td>2008</td>
</tr>
<tr>
<td>2009</td>
</tr>
<tr>
<td>2010</td>
</tr>
<tr>
<td>2011</td>
</tr>
<tr>
<td>2012</td>
</tr>
<tr>
<td>2013</td>
</tr>
<tr>
<td>2014</td>
</tr>
<tr>
<td>2015</td>
</tr>
<tr>
<td>2016</td>
</tr>
<tr>
<td><strong>avg since 08</strong></td>
</tr>
</tbody>
</table>
Blown Fuse Detection – Neutral Unbalance Protection

- Protects against over-voltages due to phase unbalance caused by fuse operation
  - For capacitor banks, relays are set to trip at 10%.
  - For harmonic filter banks, relays are set to trip due to de-tuning of filter.
- Protects against filter de-tuning due to capacitance change in filter bank caused by fuse operation

Split-Wye (Double-Wye) CT in Neutral (preferred)

Single-Wye Neutral Voltage Detection
Blown Fuse Detection, Split-Wye (CT In Neutral)

Formulas

\[ I_{\text{CURRENT THROUGH NEUTRAL CT}} = \frac{I_{\text{NOMINAL}} \times 3 \times F}{6N-F} \] (AMPS)

\[ V_{\text{REMAINING CAPACITOR VOLTAGE}} = \frac{V_{\varnothing} \times N \times 3}{3N-F} \] (VOLTS)

\[ V_{\text{CAP BANK NEUTRAL-TO-GROUND}} = \frac{V_{\varnothing} \times F}{3N-F} \] (VOLTS)

- \( I_{\text{CURRENT THROUGH NEUTRAL CT}} \) = Current in amps through CT for one or more capacitor fuse operations
- \( I_{\text{NOMINAL}} \) = Phase Current of Entire Capacitor Bank (Both Wye-Connected Banks Combined in amps)
- \( V_{\varnothing} \) = Nominal Phase-to-Neutral System Voltage (volts)
- \( F \) = Number of Failed Capacitors per Phase
- \( N \) = Number of Capacitors per Phase (this includes both sides of wye for split wye banks)
- \( V_{\text{REMAINING CAPACITOR VOLTAGE}} \) = Voltage remaining on capacitor after fuse operation (volts)
- \( V_{\text{CAP BANK NEUTRAL-TO-GROUND}} \) = Voltage from Capacitor Bank neutral to ground after fuse(s) operation.

Advantages

- Easy to have trip and alarm set points for capacitor banks (not filter banks) with more than 4 or more capacitors per phase
- Not susceptible to false tripping from system voltage unbalances
- Less costly than PT in neutral

Disadvantage

- Requires factory/field setting/calibration
- Does not protect against fuse failure
Blown Fuse Detection, Single-Wye (PT In Neutral)

Formulas

\[ V_{\text{CAP BANK NEUTRAL-TO-GROUND}} = \frac{V_\Theta \times F}{3N-F} \text{ (VOLTS)} \]

\[ V_{\text{REMAINING CAPACITOR VOLTAGE}} = \frac{V_\Theta \times N \times 3}{3N-F} \text{ (VOLTS)} \]

- \( F \) = Number of Failed Capacitors per Phase
- \( N \) = Number of Capacitors per Phase (included on both sides of wye connected capacitor bank)
- \( V_\Theta \) = Nominal Phase-to-Neutral System Voltage (volts)
- \( V_{\text{REMAINING CAPACITOR VOLTAGE}} \) = Voltage remaining on capacitor after fuse operation (volts)
- \( V_{\text{CAP BANK NEUTRAL-TO-GROUND}} \) = Voltage from Capacitor Bank neutral to ground after fuse(s) operation.

Advantages
- Easy to have trip and alarm set points for capacitor banks (not filter banks) with more than 4 or more capacitors per phase
- Neutral becomes grounded through PT winding when bank is de-energized

Disadvantage
- Susceptible to false tripping from system voltage unbalances
  - Normal line voltage unbalances
  - Unbalances due to line-to-ground faults
- Increases likelihood of switch re-strike due to TRV issues
  - Reduce probability by using L-L rated PT
- Requires factory/field setting/calibration
- Does not protect against fuse failure

Single-Wye Neutral Voltage Detection
(not recommended)
Tuning Reactors

Tuning Reactor Standards

- IEEE C57.16-2011 - *IEEE Standard for Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors*
- IEEE C57.120-2017 - *IEEE Guide for Loss Evaluation of Distribution and Power Transformers and Reactors*
- IEEE C57.12.01-2015 - *IEEE Standard for General Requirements for Dry-Type Distribution and Power Transformers*
- IEEE C57.12.91 - *IEEE Standard Test Code for Dry-Type Distribution and Power Transformers*
- IEC 60076-6 – Part 6: Reactors

Application Standards –

- IEEE Std. 1531 – *IEEE Guide for Application and Specification of Harmonic Filters*

Main Suppliers:

**Air-Core Reactor Suppliers (open-air filter designs)**
- Trench, Phoenix Electric

**Iron-Core Reactor Suppliers (metal-enclosed filter designs)**
- Power Magnetics, Control Power Transformer, Hans Van Mangoldt
Tuning Reactors, Iron-Core Vs. Air-Core

**Iron-Core**
Single-Phase, Floating Core Design

**Air-Core**
Single-Phase, Floating “Spider” Design

Fig.01. Air-Core Reactor construction

1/ Lifting lug
2/ Spanner (adjusting screws)
3/ Crossarms (spider)
4/ Terminal
5/ Insulator
6/ Extension brackets (pedestals)
Tuning Reactor Options, Iron-Core Vs. Air-Core

Iron-Core

Advantages
- No stray magnetic fields
- Easy to enclose
- Shipped installed within filter bank
  - Requires no field assembly
  - Requires no foundation
- Short lead-times ~ 6 to 8 weeks
- Well suited for high wind/seismic areas
- Lower cost
- Lower losses
- High Q ratings (typically on the order of 100 to 150)

Disadvantages
- Susceptible to saturation
  - Must account for all possible harmonics – should always be specified and designed with significant designs margins
  - When specified correctly, the iron-core reactor is equal to or better than air-core reactors.

Air-Core

Advantages
- Not susceptible to saturation
- Familiarity with some engineers

Disadvantages
- Stray magnetic fields
  - Increases footprint area ~ 1 Diameter
  - Difficult & costly to enclose
- Low Q (typically near 60)
- Shipped separate
  - Requires field assembly
  - Requires its own foundation
  - Requires its own elevating structure
- Higher cost
- Long lead-times, Up to 26 Weeks
- Higher losses
- More difficult and costly to apply in high wind and high seismic areas
Iron-core Tuning Reactors can be quite large. They can be sized to tune capacitor banks from the 1.5th harmonic to the 50th harmonic and can tune bank ratings as low as 50 kvar at 480 volts on up to over 20 MVAR at 38kV.

Metal-Enclosed Harmonic Filter Banks Utilize Iron-Core Tuning Reactors

- Capacitor bank tuning / de-tuning
  - by Power Magnetics, Mangoldt
  - 3-phase & 1-phase designs
- Nomex 410 UL, 220°C insulation system and other ratings.
- Copper/Aluminum designs based on cost and technical advantages
- Rating: 115°C rise, 60°C ambient vacuum, and other ratings.
- Limit of inductance linearity: ~220%
- Vacuum Pressure Impregnation (VPI)
  - Reduces noise from magnetic action and protects from the environment
- Conservatively rated
  - Must account for the unknown
- Heating proportional to frequency
- Attenuates switching transient
1-Phase Iron-Core Tuning Reactor Arrangement

Features
- Floating Core Design
  - Low voltage stress (similar to air-core reactor design)
  - 2 – winding design with winding barrier

Advantages
- More available ratings:
  - BIL: 60 to 200kV (max)
  - Filter 3Ø MVAR rating: 0.5 to 18 MVAR (max)
- Low stress design
  - 95% of voltage stress is across HV Insulator
  - 5% voltage stress across winding and winding to core
- Low Noise
- High Reliability

Disadvantages
- Larger footprint when compared to 3-phase core design
3-Phase Iron-Core Tuning Reactor Arrangement

Usage:
- Maximum System Voltage to 13.8kV (110kV BIL)
- Smaller filters branches (up to 2 MVAR at 13.8kV)

Features
- Grounded Core
- Phase Barriers

Advantages
- More compact (smaller footprint)
- Less costly than 3 single phase reactors

Disadvantages
- More difficult to design
  - 100% of voltage stress between winding and core
- Ratings:
  - BIL: 60 to 95kV (max)
  - Filter 3Ø MVAR rating: 0.5 to 3 MVAR (max)
- Higher Noise Levels
Voltage Stress On 13.8kV Iron-Core Filter Reactor

60Hz STEADY STATE VOLTAGES FOR 5th TUNED HARMONIC FILTER

IRON-CORE REACTOR

CURRENT LIMITING FUSES

- 3318V - 3796V

CAPACITOR

ALL INTERNAL BUS SUPPORTED ON 95kV BIL INSULATORS

95kV BIL SUPPORT INSULATOR

95kV BIL MIN.

95kV BIL MIN.

ALL INTERNAL BUS SUPPORTED ON 95kV BIL INSULATORS

95kV BIL SUPPORT INSULATOR

95kV BIL MIN.

2-BUSHING CAPACITOR WITH 95kV BIL RATING

60kV BIL MIN.

IRON-CORE

60kV BIL MIN.

OUTGOING TERMINAL IS INSULATED FROM CORE AT 60kV WINDING 2.

TURN-TO-TURN INSULATION SEE NOTE 8

CURRENT LIMITING CAPACITOR FUSE

60kV BIL MIN.

95kV BIL

60kV BIL

95kV BIL

INCOMING TERMINAL IS INSULATED FROM CORE AT 60kV WINDING 1.

WINDING-TO-WINDING INSULATION LAYERED TO PROVIDE 95kV BIL

WINDING-TO-CORE INSULATION LAYERED-TO PROVIDE 60kV BIL

MID-POINT OF IRON-CORE REACTOR IS CONNECTED TO THE IRON-CORE, NO VOLTAGE STRESS AT THIS LOCATION

IRON-CORE REACTOR IS MOUNTED ON 95kV BIL SUPPORT INSULATORS.
Voltage Stress on 34.5kV Iron-Core Reactor
Iron-Core Reactor – Gapped Core

- Inductivity requires air gap in reactor
- Many small air gaps are much better than few large air gaps

- Large air gap causes stray field
- Hot spots and forces in coils
- Increased Additional loss

- Prevents leakage
- High Linearity
- Reduces noise level
- Reduces power losses
- No hot spots
- High accuracy of tolerances

- PolyGap® Core Construction optimises
  - air gap size and
  - distribution
**Iron-Core Tuning Reactor Ratings**

**Key Ratings**
- # of Phases
- Inductance/Reactance at nominal frequency
- Nominal frequency
- Nominal System Voltage
  - determines voltage class of insulation (BIL, withstand), & winding margins
- RMS Current
  - For rating winding ampacity
  - Winding cooling requirements
- Harmonic Current Spectrum
  - Peak current rating (summation of harmonic currents to determine flux density of core).
  - Heating in Core to determine cooling requirements
- Taps
  - To adjust tuning point for component tolerance.
  - To adjust kvar
  - To adjust tuning point for reliability (for example a 5,7 tuning point).
- Ambient Temperature (normally 60°C for metal-enclosed filters)
- Q Rating (normally very high for iron-core (near 100)).

**Ratings Table**

<table>
<thead>
<tr>
<th>Current Ratings</th>
<th>Design &amp; Construction Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harm #</td>
<td>Amps</td>
</tr>
<tr>
<td>1</td>
<td>314.1</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>0</td>
</tr>
<tr>
<td>23</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>29</td>
<td>0</td>
</tr>
<tr>
<td>31</td>
<td>0</td>
</tr>
<tr>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>37</td>
<td>0</td>
</tr>
<tr>
<td>41</td>
<td>0</td>
</tr>
<tr>
<td>43</td>
<td>0</td>
</tr>
<tr>
<td><strong>RMS:</strong></td>
<td><strong>434.4</strong></td>
</tr>
</tbody>
</table>
Air-Core Reactor Mounting Arrangements

Stacked Reactor Arrangement

Unstacked Reactor Arrangement
Air-Core Reactor – Radial Magnetic Clearance Requirements

Installation Diagram
(magnetic field clearance requirements)

Notes:
- Stray magnetic fields are significant and can induce currents in metallic parts that may cause thermal and electrodynamic effects. Nearby metal structures, electronics equipment, rebar, etc. shall be located in areas where the effect will not create excessive heating.
- \( D_e \approx 2 \times \) coil diameter
- \( MC_1 \approx 1.1 \times \) coil diameter (metallic parts not forming closed loops – as measured from center of reactor)
- \( MC_2 \approx 1.5 \times \) coil diameter (metallic parts forming closed loops – as measured from center of reactor)

Air-core tuning reactors have significant footprint requirements
(typical coil diameter: \( \approx 5 \) feet - thus a 15’ diameter is required for MC2 clearances)
Air-Core Reactor – Axial/Radial Magnetic Clearance Requirements

(magnetic field clearance requirements)
Side View

**Notes:**

- **Sides – Radial Distance**
  - $MC_1 \approx 1.1 \times \text{coil diameter}$ (metallic parts not forming closed loops – as measured from center of reactor)
  - $MC_2 \approx 1.5 \times \text{coil diameter}$ (metallic parts forming closed loops – as measured from center of reactor)

- **Top/Bottom – Axial Distance**
  - $MC_1 \approx 0.5 \times \text{coil diameter}$ (metallic parts not forming closed loops – as measured from center of reactor)
  - $MC_2 \approx 1.0 \times \text{coil diameter}$ (metallic parts forming closed loops – as measured from center of reactor)

---

A: reactor outer surface  
Ds: reactor diameter  
keep metallic parts not forming closed loops outside $MC_1$  
keep metallic parts forming closed loops outside $MC_2$
High-Pass Filter Resistors

HP Resistor Standards
- No Standard directly applies

Application Standards –
- IEEE Std. 1531 – *IEEE Guide for Application and Specification of Harmonic Filters*

Main Suppliers:
Post Glover, Avtron Power Resistors

Preferred Type:
Low Inductance, Stainless Steel Stamped Grid Design

Typical Ratings:
Minimum: 20kW/Phase
Maximum: 150kW – 200kW / Phase
**High-Pass (HP) Filter Resistor – Rating Calculation**

- **R** = Resistance = Based on Damping Factor (DF) of filter (Ohms)
- **$V_{R(n)}$** = Harmonic voltage across resistor is calculated based on parallel impedance of $JX_{L(n)}$ and R multiplied by expected harmonic filter current $I_{filter(n)}$ (Volts)

\[ V_{R(n)} = I_{filter(n)} \times \frac{1}{\sqrt{\frac{1}{R^2} + \frac{1}{X_{L(n)}}}} \] (Volts)

- **$I_{R(n)}$** is obtained by dividing $V_{R(n)}/R$ (Amps)
- **$I_{Resistor RMS Current}$** is obtained by taking the square root of the sum of squares of all harmonic currents flowing in resistor

\[ I_{Resistor RMS CURRENT} = \sqrt{\sum_{n=1}^{n} I_{R(n)}^2} \] (Amps)

- The single-phase power rating of the resistor is calculated by squaring the RMS current rating of the resistor and multiplying by R.

\[ P_{Resistor} = I_{Resistor RMS CURRENT}^2 \times R \]
C-High-Pass (C-HP) Filter Resistor – Rating Calculation

- **R** = Resistance = Based on Damping Factor (DF) of filter (Ohms)
- **V<sub>R(n)</sub>** = Harmonic voltage across resistor is calculated based on parallel impedance of JX<sub>L(n)</sub>, R, and X<sub>CA(n)</sub> multiplied by expected harmonic filter current I<sub>filter(n)</sub> (Volts)

\[
V_{R(n)} = I_{filter (n)} \times \frac{1}{\sqrt{\frac{1}{R^2} + \left(\frac{1}{X_L(n) - X_C(n)}\right)^2}} \quad \text{(Volts)}
\]

- **I<sub>R(n)</sub>** is obtained by dividing **V<sub>R(n)</sub>/R** (Amps)
- **I<sub>Resistor RMS Current</sub>** is obtained by taking the square root of the sum of squares of all harmonic currents flowing in resistor

\[
I_{Resistor RMS CURRENT} = \sqrt{\sum_{n=1}^{N} I_{R(n)}^2} \quad \text{(Amps)}
\]

- The single-phase power rating of the resistor is calculated by squaring the RMS current rating of the resistor and multiplying by **R**.

\[
P_{Resistor} = I_{Resistor RMS CURRENT}^2 \times R
\]
High-pass Filter Resistor

Specify
- System Voltage, BIL, Single-Phase Resistance, Elevation, RMS Current Rating of Resistor
- Specify Stainless Steel Stamped Grid Type Resistor Elements
- Cooling: Natural Convection
- Roof-mounted / Rack-mounted in 409/304/316 stainless steel enclosure depending on type of filter
  - Enclosure not painted
- Power / current ratings should be doubled to account for unforeseen harmonic conditions
- Ohms are based on Damping Factor (DF) requirement of filter
- Number of series elements should be equal to $V_{LN}/5kV$ to compensate for transient voltage during energization.

Edge wound and wire wound resistors should be avoided if possible
Stamped Grid Resistors

- Multiple taps on each grid for resistance flexibility
- Welded connections between grid plates
- No maintenance

Cross Section View
Other Design Details

• Switching
• Protection
• Control
• Arc Flash Mitigation
Arc Resistant Enclosure Design
Arc Flash Hazard Mitigation – Design Strategies

- **Technology that Reduces Arcing Time and Incident Energy**
  - Current limiting fuses
  - ABB UFES system
  - Arc flash detection relays
  - Bus differential relays

- **Design Features that Reduce Exposure to Arc Flash Hazard**
  - Locate equipment outdoors
  - Delayed switching
  - Arc resistant enclosure designs built to IEEE C37.20.7 requirements
  - Remote switching | remote racking
  - Remote protection & control system
• Design Practices that Reduce Probability of Arc Flash Event
  o Key interlocks
  o Proper choice of capacitor switching device
  o Fuse failure protection
  o Windows
  o Condensation control with heaters
  o Rodent screens/floor
  o Signage
  o Insulated bus bars
  o Increase BIL rating
  o Smoke detectors
  o Partial discharge monitoring
  o Infrared inspection windows
NEPSI Resources

- Contact NEPSI about your application
  - Application Engineers
  - Firm / Budgetary Quotes, Drawings, etc.
- Web – nepsi.com
  - Product literature
  - Component Literature
  - Guide form specifications
  - Case studies
  - Calculators
  - Request for Quote Forms
  - Spread Sheet tools
  - YouTube / How-to Videos