NEPSI

Northeast Power Systems, Inc.

Medium-Voltage Metal-Enclosed Products

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

Presentation On Harmonic Filter Design

Presented by Paul Steciuk

Harmonic Filter Design - Summary of Presentation

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)

Harmonic Filter Design – Presentation Outline (Continued)

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

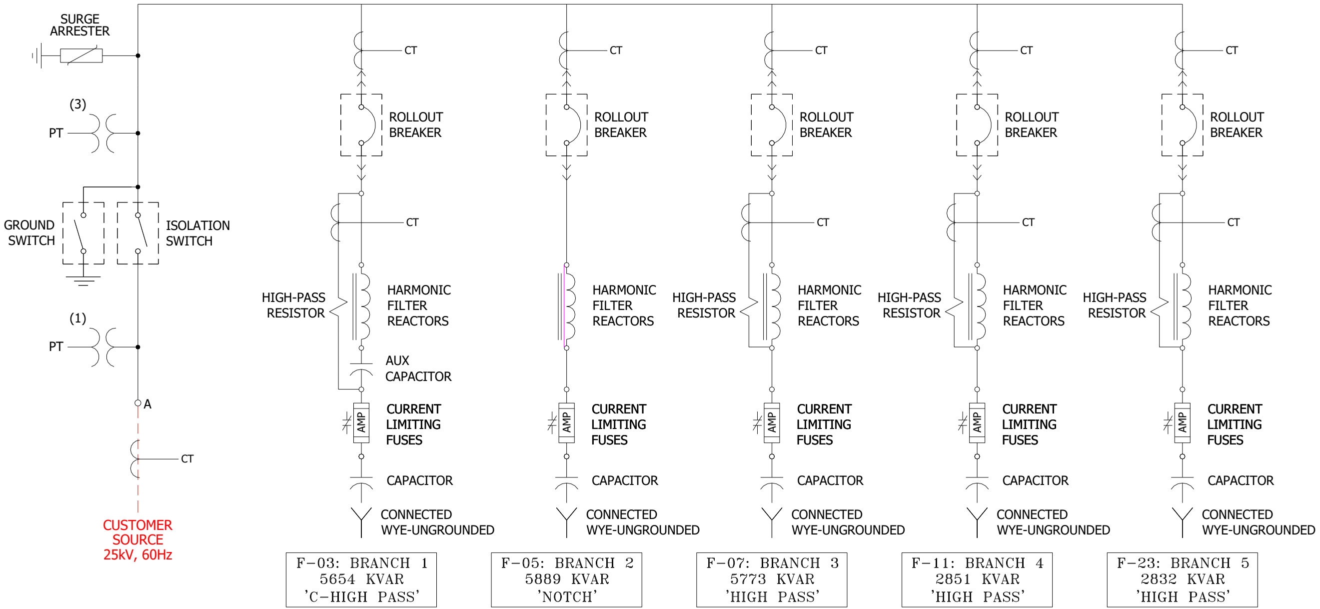
C-High Pass, High Pass, and Notch Filter Branches

23 MVAR, 24.9 kV, 5-Stage, All-Inclusive Harmonic Filter System

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

Background

Large Harmonic Filter One-Line Diagram



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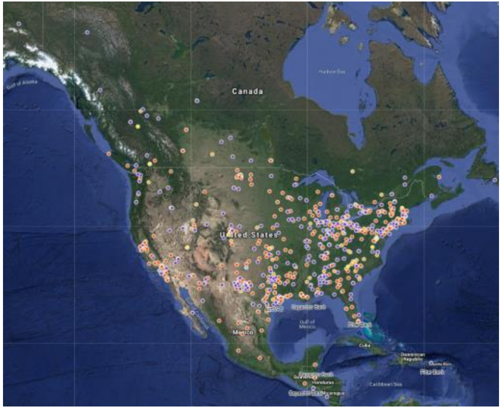
Northeast Power Systems, Inc.

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

<u>NEPSI also brand labels for ABB, GE, Schneider, Eaton and other large electrical brands</u>

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Technical Presentation

Harmonic Filter Design

Presented by Paul Steciuk
Paul.Steciuk@NEPSI.COM

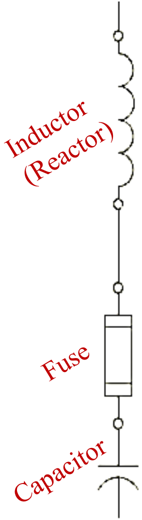
Harmonic Filters – What Are They and What Do They Do?

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

Metal-Enclosed

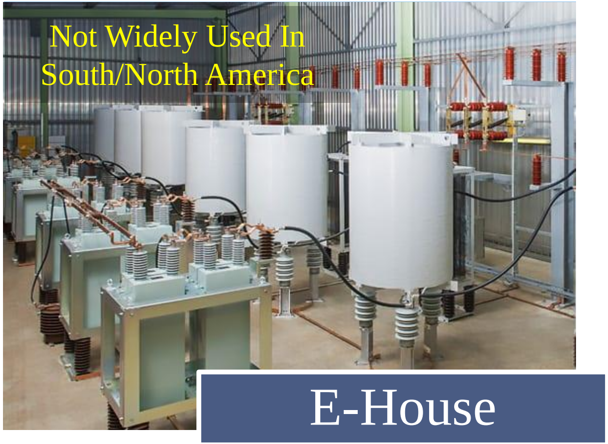
Open-Air

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

Harmonic Filter Configuration Options

Metal-Enclosed



Not Widely Used In South/North America

E-House

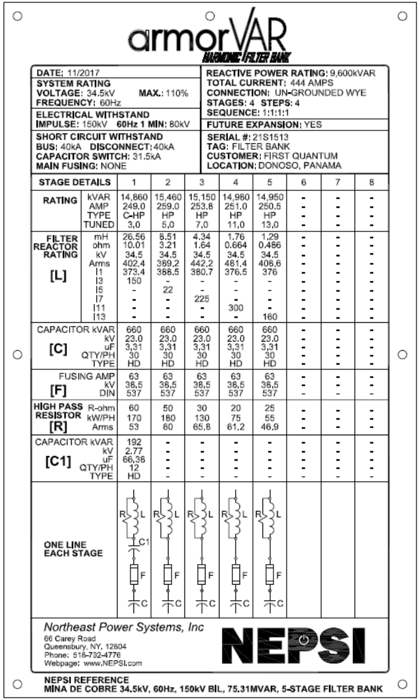
When all costs are considered, including engineering & procurement, integration, site preparation, installation, commissioning, maintenance, and liability,

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)

Typical Harmonic Filter System Nameplate



armorVAR
HARMONIC FILTER BANK

DATE: 11/2017
SYSTEM RATING
VOLTAGE: 34.5kV MAX.: 110%
FREQUENCY: 60Hz
ELECTRICAL WITHSTAND
IMPULSE: 150kV 60Hz 1 MIN: 80kV
SHORT CIRCUIT WITHSTAND
BUS: 40kA DISCONNECT: 40kA
CAPACITOR SWITCH: 31.5kA
MAIN FUSING: NONE

REACTIVE POWER RATING: 9,600kVAR
TOTAL CURRENT: 444 AMPS
CONNECTION: UN-GROUNDED WYE
STAGES: 4 STEPS: 4
SEQUENCE: 1:1:1:1
FUTURE EXPANSION: YES
SERIAL #: 21S1513
TAG: FILTER BANK
CUSTOMER: FIRST QUANTUM
LOCATION: DONOSO, PANAMA

STAGE DETAILS		1	2	3	4	5	6	7	8
RATING	kVAR	14,860	15,460	15,150	14,980	14,950	-	-	-
	AMP	249.0	259.0	253.8	251.0	250.5	-	-	-
	TYPE	C-HP	HP	HP	HP	HP	-	-	-
	TUNED	3,0	5,0	7,0	11,0	13,0	-	-	-
FILTER REACTOR RATING [L]	mH	26.56	8.51	4.34	1.76	1.29	-	-	-
	ohm	10.01	3.21	1.64	0.664	0.486	-	-	-
	kV	34.5	34.5	34.5	34.5	34.5	-	-	-
	Arms	402.4	369.2	442.2	481.4	406.6	-	-	-
	I1	373.4	388.5	380.7	376.5	376	-	-	-
	I3	150	-	-	-	-	-	-	-
	I5	-	22	-	-	-	-	-	-
	I7	-	-	225	-	-	-	-	-
	I11	-	-	-	300	-	-	-	-
	I13	-	-	-	-	160	-	-	-
CAPACITOR [C]	kVAR	660	660	660	660	660	-	-	-
	kV	23.0	23.0	23.0	23.0	23.0	-	-	-
	uF	3,31	3,31	3,31	3,31	3,31	-	-	-
	QTY/PH	30	30	30	30	30	-	-	-
	TYPE	HD	HD	HD	HD	HD	-	-	-
FUSING [F]	AMP	63	63	63	63	63	-	-	-
	kV	38,5	38,5	38,5	38,5	38,5	-	-	-
	DIN	537	537	537	537	537	-	-	-
HIGH PASS RESISTOR [R]	R-ohm	60	50	30	20	25	-	-	-
	kW/PH	170	180	130	75	55	-	-	-
	Arms	53	60	65.8	61.2	46.9	-	-	-
CAPACITOR [C1]	kVAR	192	-	-	-	-	-	-	-
	kV	2.77	-	-	-	-	-	-	-
	uF	66,38	-	-	-	-	-	-	-
	QTY/PH	12	-	-	-	-	-	-	-
	TYPE	HD	-	-	-	-	-	-	-
ONE LINE EACH STAGE									

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NEPSI

NEPSI REFERENCE
MINA DE COBRE 34.5kV, 60Hz, 150kV BIL, 75.31MVAR, 5-STAGE FILTER BANK

How Are Harmonic Filter Ratings Determined?

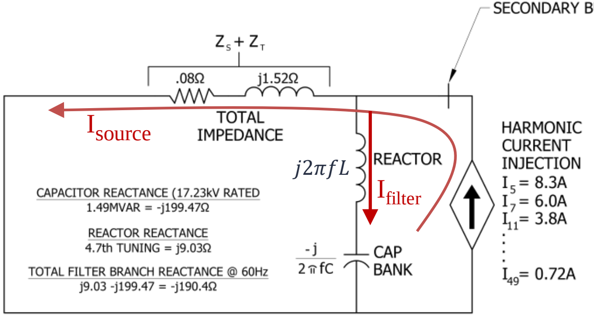
Filter Ratings

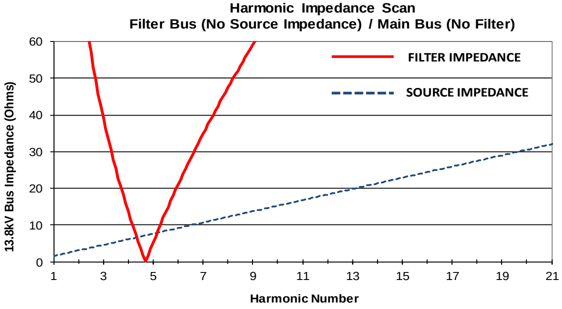
- Power System Studies
  - Load Flow Analysis
    - Determines reactive power rating of filter (MVAR)
  - Harmonic Analysis
    - Determines filter tuning
    - Determines expected harmonic current flow into filter branch(s)
    - Filter type (Notch, C-HP, HP)
  - Based on above studies, L, R, C Filter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

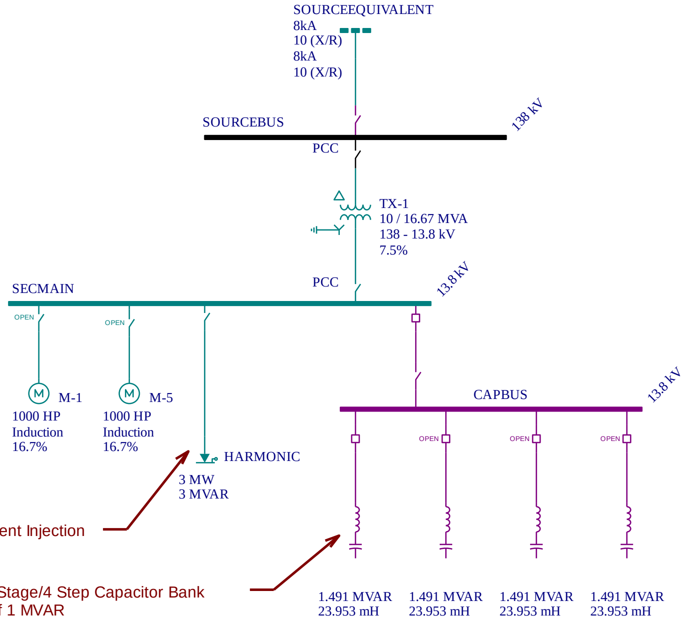
Filter Component Ratings (Capacitors | Reactors | Resistors)

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

Harmonic Filter – Basic Concepts



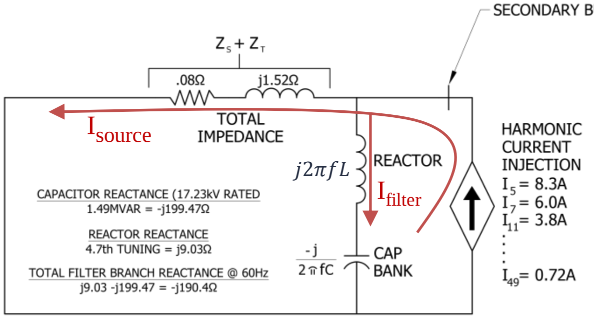


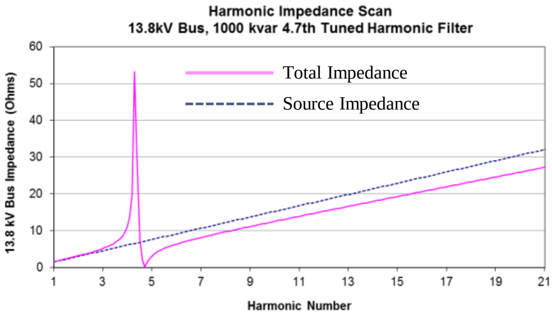


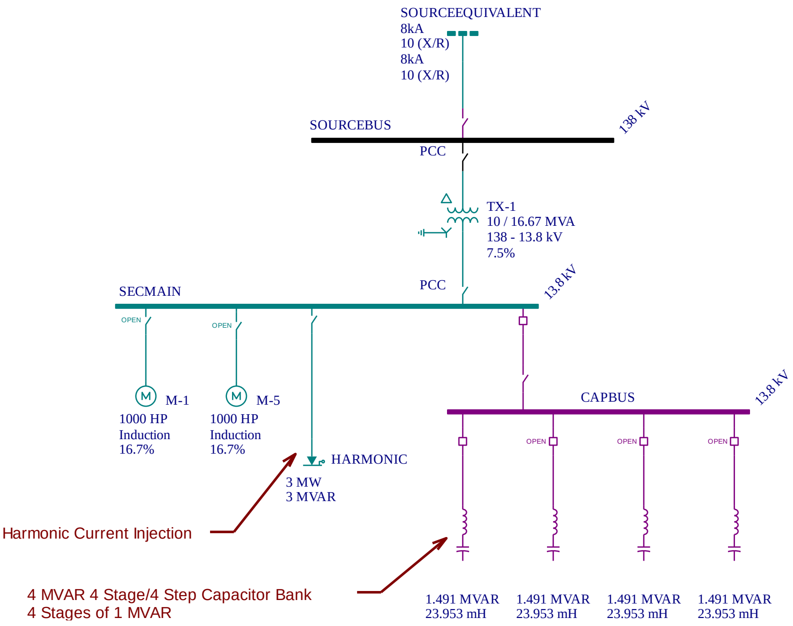
Harmonic Current Injection

4 MVAR 4 Stage/4 Step Capacitor Bank
4 Stages of 1 MVAR

Harmonic Filter – Basic Concepts



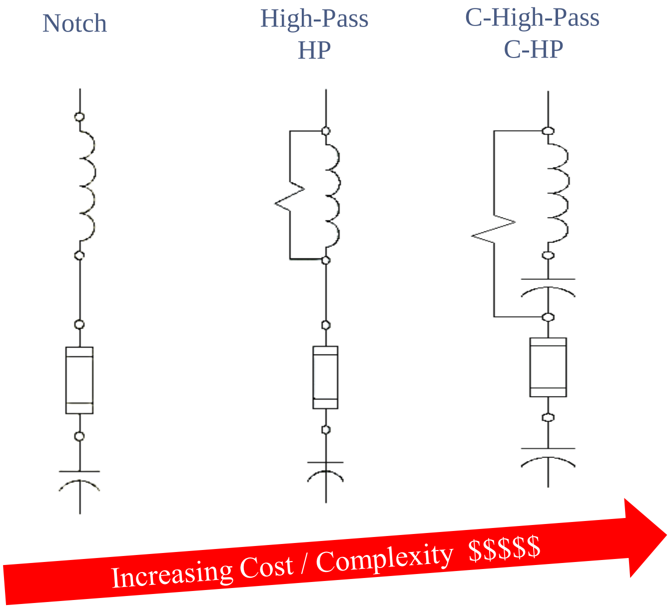




Harmonic Current Injection

4 MVAR 4 Stage/4 Step Capacitor Bank
4 Stages of 1 MVAR

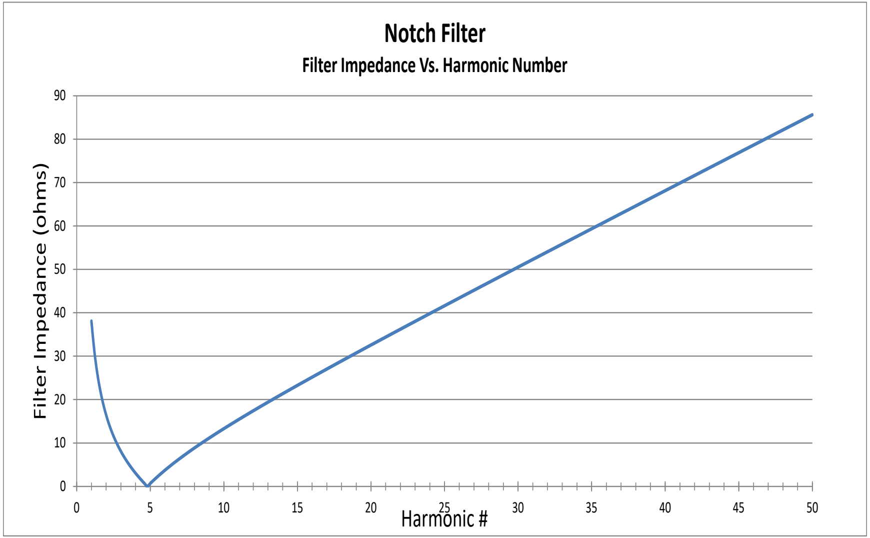
Most Common Filter Types Used at Medium Voltage Level



Application Considerations

- **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

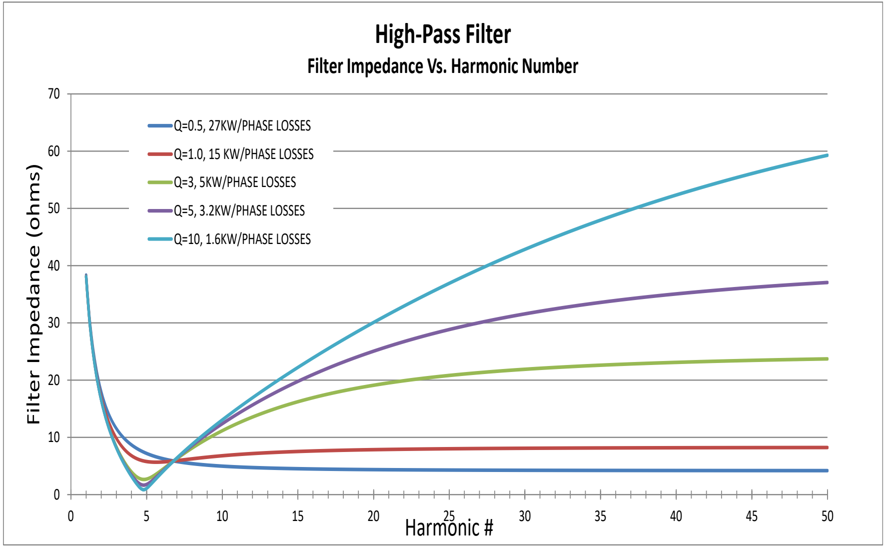
Notch Tuned Filter

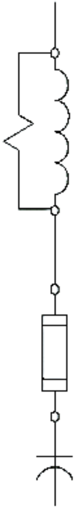


Key Characteristics

- 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)

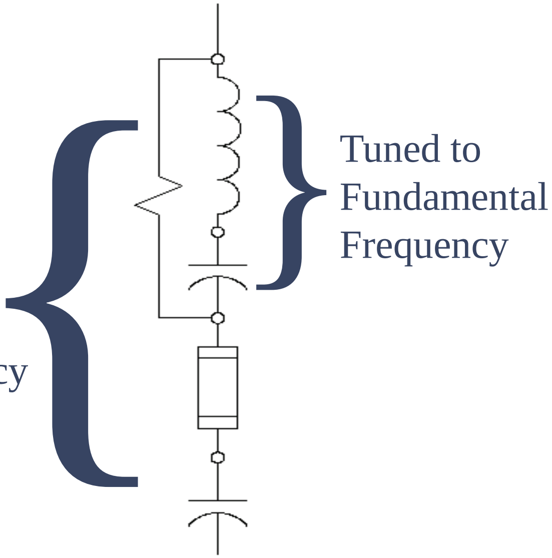




Key Characteristics

- 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.

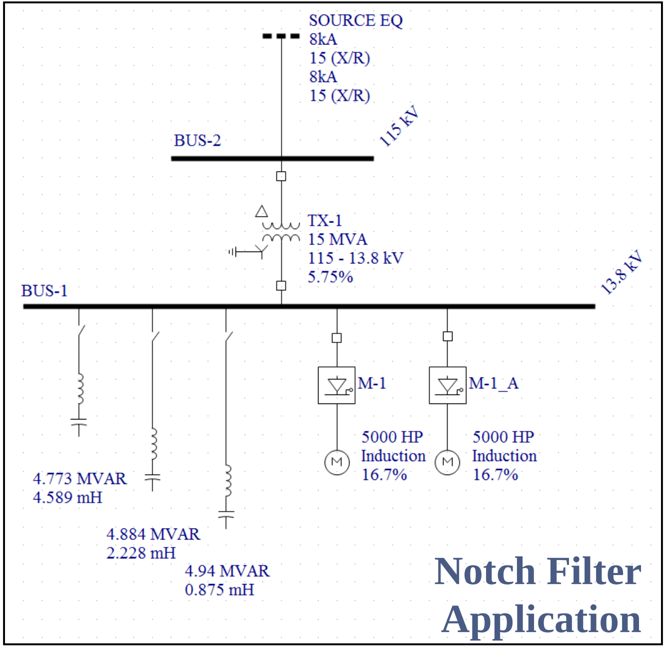
C-High-Pass (C-HP) Tuned Filter (Damped Harmonic Filter)



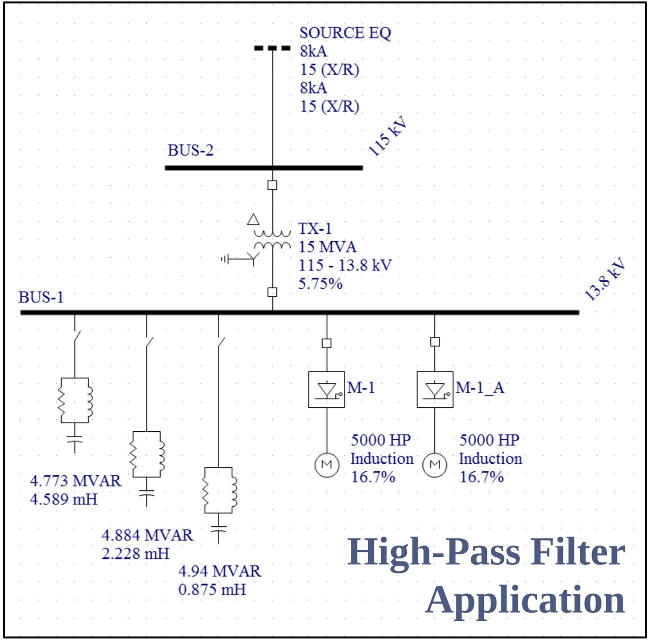
Key Characteristics

- 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

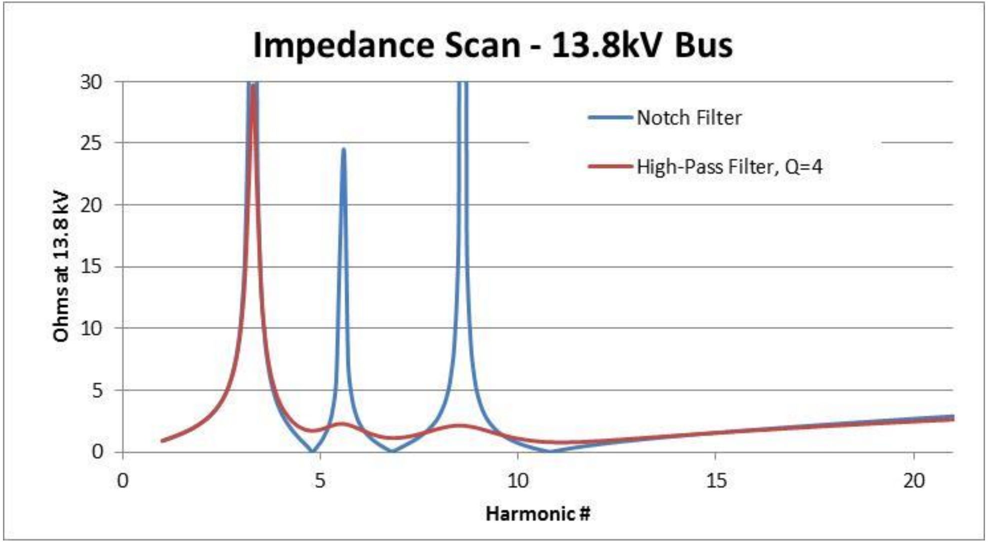


Notch Filter Application



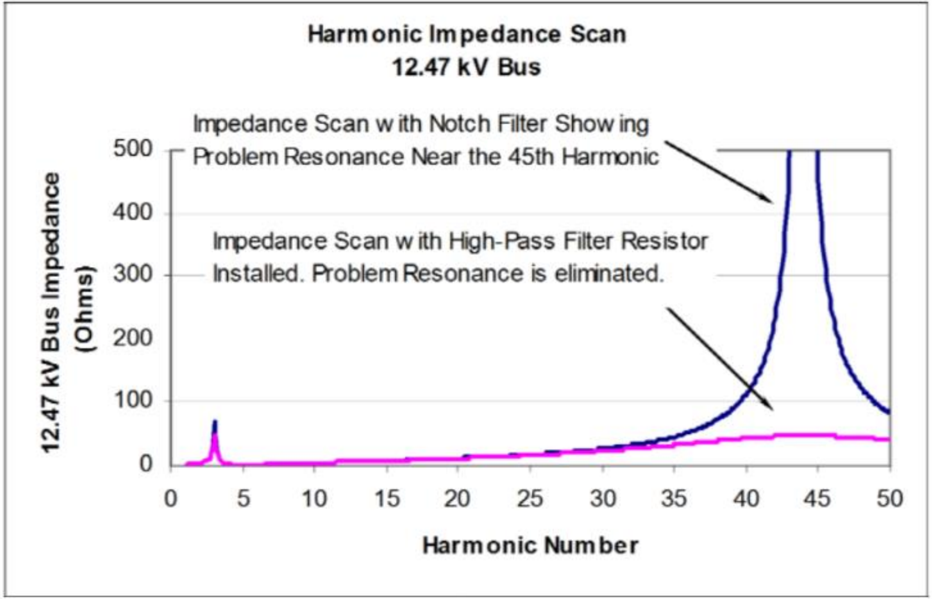
High-Pass Filter Application

High-Pass Vs. Notch Filter Impedance Scan Comparison



- 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

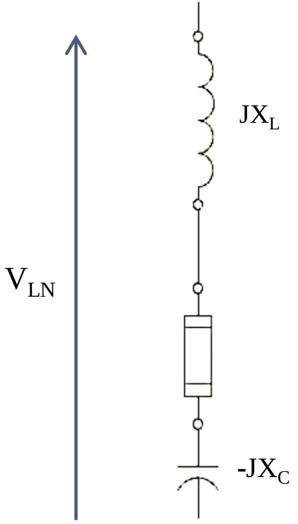
High-Pass Filters (C-HP & HP) Dampen Resonance Conditions



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)



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

$$\text{kV}_{LLSYS} = Filter\ Nominal\ Line-to-Line\ Voltage\ Rating\ (KV) = 13.8\ kV$$

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

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

$$X_L = \frac{X_C}{h^2} = \frac{199.47}{4.7^2} = 9.03\ ohms$$

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

$$Q_{RATED\ PER\ PHASE\ (MVAR)} = \frac{(V_{CAP\ RATING})^2}{X_C} = \frac{(9.54)^2}{199.47} = 0.456\ MVAR/Phase$$

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

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

h = *Tuning Point*

X_c = *Capacitive Reactance of Capacitor* (ohms)

X_L = *Inductive Reactance* of Reactor (ohms)

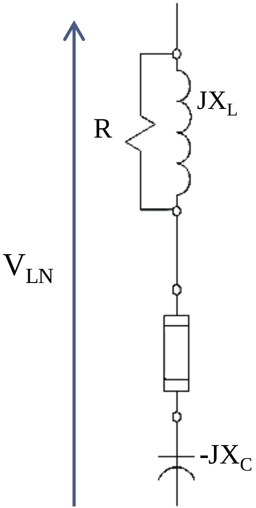
f = *Filter System Fundamental Frequency* (Hz)

$$C = \frac{1}{2\pi f X_c} \qquad L = \frac{X_L}{2\pi f}$$

I_n = Current in Amps at Each Harmonic

Tuning Calculation (X_L, X_C, L, C, R) – HP Filter Design

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



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

h = *Tuning Point*

X_c = *Capacitive Reactance of Capacitor* (Ohms)

X_L = *Inductive Reactance* of Reactor (Ohms)

f = *Filter System Fundamental Frequency* (Ohms)

R = Damping Resistance (Ohms)

DF= Damping Factor

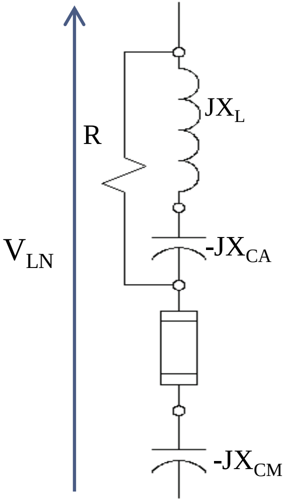
$$C = \frac{1}{2\pi f X_c} \text{ (f)} \qquad L = \frac{X_L}{2\pi f}\ (H)$$

$$\text{R} = DF \times x_L \times h\ (ohms)$$

I_n = Current in Amps at Each Harmonic

Tuning Calculation (X_L, X_C, L, C, R) – C-HP Filter Design

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



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

$$\mathrm{k}V_{LLSYS} = Filter\ Nominal\ Line - to - Line\ Voltage\ Rating\ (KV) = 13.8\ kV$$

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

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

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

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

$h = Tuning\ Point$

X_{CA} = *Capacitive Reactance of Aux Capacitor* Group (Ohms)

X_{CM} = *Capacitive Reactance of Main Capacitor* Group (Ohms)

X_L = *Inductive Reactance* of Reactor (Ohms)

f = *Filter System Fundamental Frequency* (Ohms)

R = Damping Resistance (Ohms)

DF= Damping Factor

$$C = \frac{1}{2\pi f X_c}\ (\mathrm{f}) \qquad L = \frac{X_L}{2\pi f}\ (H)$$

$$\mathrm{R} = DF \times x_L \times h\ (ohms)$$

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

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

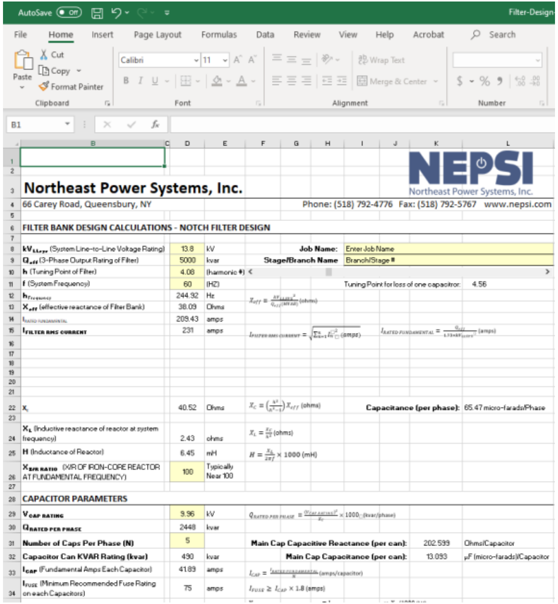
$$I_{RATED\ FUNDAMENTAL} = \frac{Q_{eff}}{1.73 \times kV_{LLSYS}} \times 1000 = \frac{1.0}{1.73 \times 13.8} \times 1000 = 41.88\ amps$$

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

I_n = Current in Amps at Each Harmonic

Spreadsheet Tools Speed Up & Confirm Design

The Easy Way



Northeast Power Systems, Inc.

66 Carey Road, Queensbury, NY — Phone: (518) 792-4776 Fax: (518) 792-5767 www.nepsi.com

FILTER BANK DESIGN CALCULATIONS - NOTCH FILTER DESIGN

$kV_{LL sys}$ (System Line-to-Line Voltage Rating)	13.8	kV	**Job Name:** Enter Job Name
Q_{eff} (3-Phase Output Rating of Filter)	5000	kvar	**Stage/Branch Name** Branch/Stage #
h (Tuning Point of Filter)	4.08	(harmonic #)	
f (System Frequency)	60	(HZ)	Tuning Point for loss of one capacitor: 4.56
$h_{Frequency}$	244.92	Hz	
X_{eff} (effective reactance of Filter Bank)	38.09	Ohms	$X_{eff} = \frac{kV_{LLsys}^2}{Q_{eff}(MVAR)}$ (ohms)
$I_{RATED\ FUNDAMENTAL}$	209.43	amps	
$I_{FILTER\ RMS\ CURRENT}$	231	amps	$I_{FILTER\ RMS\ CURRENT} = \sqrt{\sum_{h=1}^{n} I_h^2}$ (amps) $I_{RATED\ FUNDAMENTAL} = \frac{Q_{eff}}{1.73 \times kV_{LLsys}}$ (amps)
X_C	40.52	Ohms	$X_C = \left(\frac{h^2}{h^2-1}\right) X_{eff}$ (ohms) **Capacitance (per phase):** 65.47 micro-farads/Phase
X_L (Inductive reactance of reactor at system frequency)	2.43	ohms	$X_L = \frac{X_C}{h^2}$ (ohms)
H (Inductance of Reactor)	6.45	mH	$H = \frac{X_L}{2\pi f} \times 1000$ (mH)
$X_{R/R\ RATIO}$ (X/R OF IRON-CORE REACTOR AT FUNDAMENTAL FREQUENCY)	100	Typically Near 100	
CAPACITOR PARAMETERS			
$V_{CAP\ RATING}$	9.96	kV	$Q_{RATED\ PER\ PHASE} = \frac{(V_{CAP\ RATING})^2}{X_C} \times 1000$ (kvar/phase)
$Q_{RATED\ PER\ PHASE}$	2448	kvar	
Number of Caps Per Phase (N)	5		**Main Cap Capacitive Reactance (per can):** 202.599 Ohms/Capacitor
Capacitor Can KVAR Rating (kvar)	490	kvar	**Main Cap Capacitance (per can):** 13.093 μF (micro-farads)/Capacitor
I_{CAP} (Fundamental Amps Each Capacitor)	41.89	amps	$I_{CAP} = \frac{I_{RATED\ FUNDAMENTAL}}{N}$ (amps/capacitor)
I_{FUSE} (Minimum Recommended Fuse Rating on each Capacitors)	75	amps	$I_{FUSE} \geq I_{CAP} \times 1.8$ (amps)

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.
- NEPSI Spreadsheet tool available at: http://nepsi.com/resources/spreadsheet-tools/
    - 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

- IEEE Std. 18-2002, *IEEE Standard for Shunt Power Capacitors*
- 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. 1036 – 1992, *IEEE Guide for Application of Shunt Power Capacitors*
- IEEE Std. C37.99-2000, *IEEE Guide for Protection of Shunt Capacitor Banks*
- IEEE Std. 1531 – *IEEE Guide for Application and Specification of Harmonic Filters*

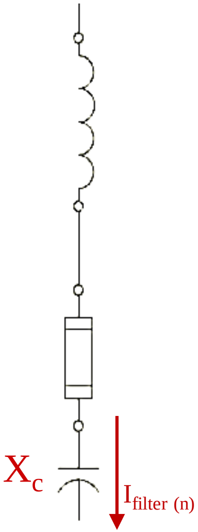
Main Suppliers:
ABB, Cooper Power (Eaton), General Electric (GE), Vishay

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 filer.

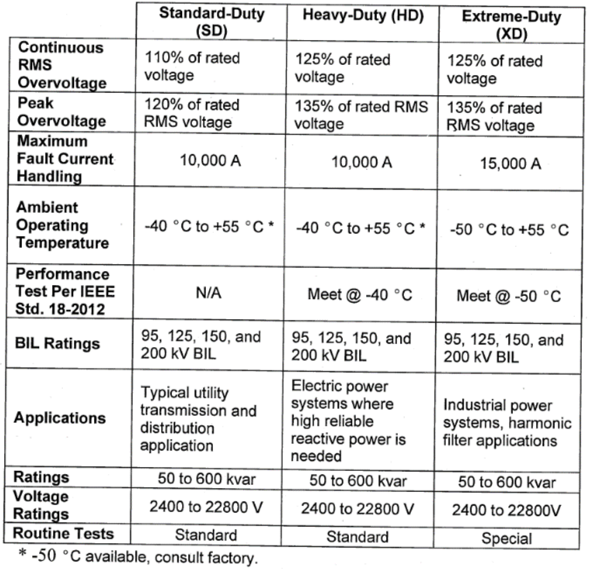
Capacitor Standard Maximum Ratings	Capacitor Duty Rating in Filter
• 110% of rated RMS voltage	$V_{CAP\ RMS\ VOLTAGE} = \sqrt{\sum_{n=1}^{n} V_{CAP\ HARMONIC\ VOLTAGE\ (n)}{}^{2}}$
• 120% of rated peak voltage, i.e. peak voltage not exceeding 1.2 x (square root of two or 1.414) x rated rms voltage, including harmonics, but excluding transients	$V_{CAP\ PEAK\ VOLTAGE} = 1.414 \times \sum_{n=1}^{n} V_{CAP\ HARMONIC\ VOLTAGE\ (n)}$
• 135% of nominal RMS current based on rated kvar and rated voltage	$I_{CAP\ RMS\ CURRENT} = \sqrt{\sum_{n=1}^{n} I_{filter\ (n)}^{2}}$
• 135% of rated kvar	$Q_{\ CAPACITOR} = \sum_{n=1}^{n} \frac{X_c}{n} \times I_{filter\ (n)}^{2}/1000$

X_C = Fundamental Capacitive Reactance of Capacitor

$$V_{CAP\ HARMONIC\ VOLTAGE\ (n)} = \frac{X_C}{n} \times I_{filter\ (n)}$$

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



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

* -50 °C available, consult factory.

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

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.

Standard Capacitor Ratings

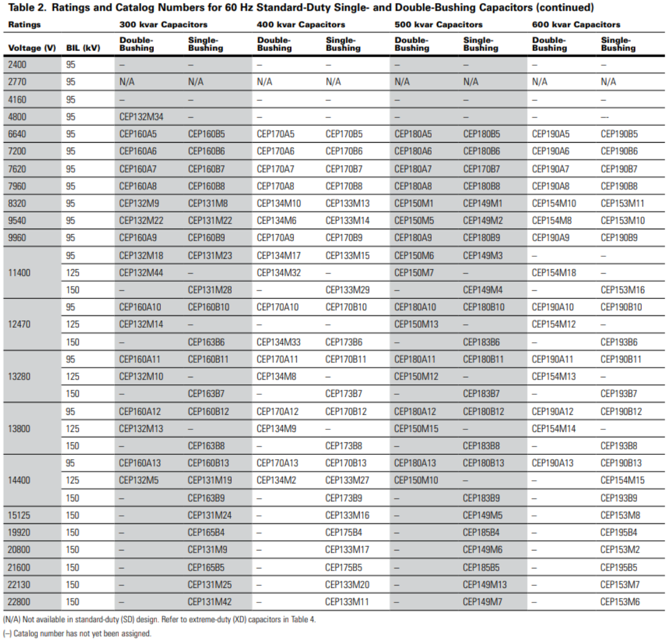


Table 2. Ratings and Catalog Numbers for 60 Hz Standard-Duty Single- and Double-Bushing Capacitors (continued)

Ratings		300 kvar Capacitors		400 kvar Capacitors		500 kvar Capacitors		600 kvar Capacitors	
Voltage (V)	BIL (kV)	Double-Bushing	Single-Bushing	Double-Bushing	Single-Bushing	Double-Bushing	Single-Bushing	Double-Bushing	Single-Bushing
2400	95	–	–	–	–	–	–	–	–
2770	95	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4160	95	–	–	–	–	–	–	–	–
4800	95	CEP132M34	–	–	–	–	–	–	–-
6640	95	CEP160A5	CEP160B5	CEP170A5	CEP170B5	CEP180A5	CEP180B5	CEP190A5	CEP190B5
7200	95	CEP160A6	CEP160B6	CEP170A6	CEP170B6	CEP180A6	CEP180B6	CEP190A6	CEP190B6
7620	95	CEP160A7	CEP160B7	CEP170A7	CEP170B7	CEP180A7	CEP170B7	CEP190A7	CEP190B7
7960	95	CEP160A8	CEP160B8	CEP170A8	CEP170B8	CEP180A8	CEP180B8	CEP190A8	CEP190B8
8320	95	CEP132M9	CEP131M8	CEP134M10	CEP133M13	CEP150M1	CEP149M1	CEP154M10	CEP153M11
9540	95	CEP132M22	CEP131M22	CEP134M6	CEP133M14	CEP150M5	CEP149M2	CEP154M8	CEP153M10
9960	95	CEP160A9	CEP160B9	CEP170A9	CEP170B9	CEP180A9	CEP180B9	CEP190A9	CEP190B9
11400	95	CEP132M18	CEP131M23	CEP134M17	CEP133M15	CEP150M6	CEP149M3	–	–
	125	CEP132M44	–	CEP134M32	–	CEP150M7	–	CEP154M18	–
	150	–	CEP131M28	–	CEP133M29	–	CEP149M4	–	CEP153M16
12470	95	CEP160A10	CEP160B10	CEP170A10	CEP170B10	CEP180A10	CEP180B10	CEP190A10	CEP190B10
	125	CEP132M14	–	–	–	CEP150M13	–	CEP154M12	–
	150	–	CEP163B6	CEP134M33	CEP173B6	–	CEP183B6	–	CEP193B6
13280	95	CEP160A11	CEP160B11	CEP170A11	CEP170B11	CEP180A11	CEP180B11	CEP190A11	CEP190B11
	125	CEP132M10	–	CEP134M8	–	CEP150M12	–	CEP154M13	–
	150	–	CEP163B7	–	CEP173B7	–	CEP183B7	–	CEP193B7
13800	95	CEP160A12	CEP160B12	CEP170A12	CEP170B12	CEP180A12	CEP180B12	CEP190A12	CEP190B12
	125	CEP132M13	–	CEP134M9	–	CEP150M15	–	CEP154M14	–
	150	–	CEP163B8	–	CEP173B8	–	CEP183B8	–	CEP193B8
14400	95	CEP160A13	CEP160B13	CEP170A13	CEP170B13	CEP180A13	CEP180B13	CEP190A13	CEP190B13
	125	CEP132M5	CEP131M19	CEP134M2	CEP133M27	CEP150M10	–	–	CEP154M15
	150	–	CEP163B9	–	CEP173B9	–	CEP183B9	–	CEP193B9
15125	150	–	CEP131M24	–	CEP133M16	–	CEP149M5	–	CEP153M8
19920	150	–	CEP165B4	–	CEP175B4	–	CEP185B4	–	CEP195B4
20800	150	–	CEP131M9	–	CEP133M17	–	CEP149M6	–	CEP153M2
21600	150	–	CEP165B5	–	CEP175B5	–	CEP185B5	–	CEP195B5
22130	150	–	CEP131M25	–	CEP133M20	–	CEP149M13	–	CEP153M7
22800	150	–	CEP131M42	–	CEP133M11	–	CEP149M7	–	CEP153M6

(N/A) Not available in standard-duty (SD) design. Refer to extreme-duty (XD) capacitors in Table 4.

(–) Catalog number has not yet been assigned.

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.

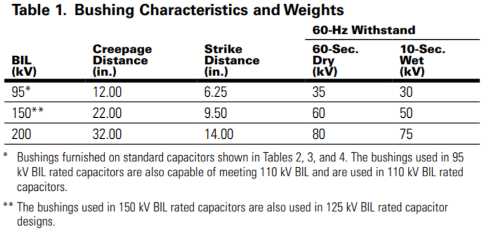


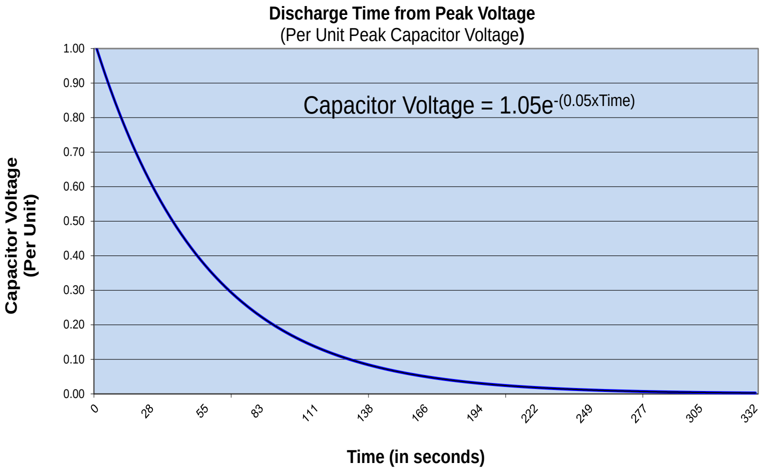
Table 1. Bushing Characteristics and Weights

BIL (kV)	Creepage Distance (in.)	Strike Distance (in.)	60-Hz Withstand	
			60-Sec. Dry (kV)	10-Sec. Wet (kV)
95*	12.00	6.25	35	30
150**	22.00	9.50	60	50
200	32.00	14.00	80	75

* 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.

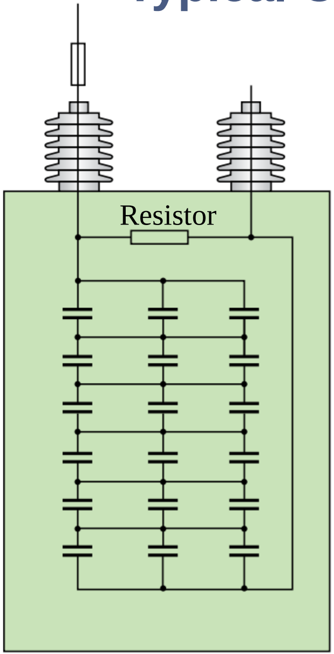
Standard Capacitor Discharge Curve



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

- 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

Typical Capacitor Construction – Externally Fused



Typical Construction

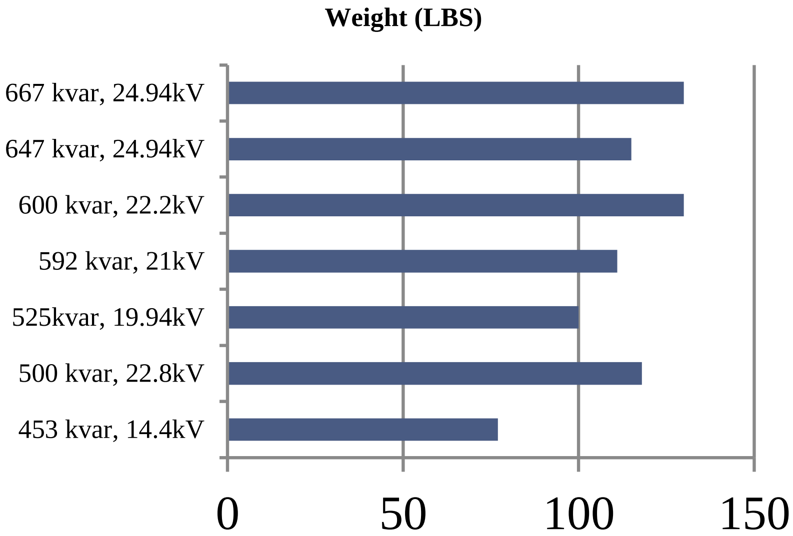
- Capacitors are built of series and parallel sections to obtain desired kvar and voltage rating.
- Sections typically have a 2000 volt rating.
- 1-Bushing and 2-Bushing designs
- Are filled with a non-PCB dielectric fluid, about 5 Gallons (18.9 Liters) per capacitor
- Typically weigh less than 120 Pounds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

$$Capacitance\ Increase = \frac{(\#\ of\ Series\ Sections)}{(\#\ of\ series\ section\ failures) - (\#\ of\ failed\ sections)}$$

Typical Capacitor Weight

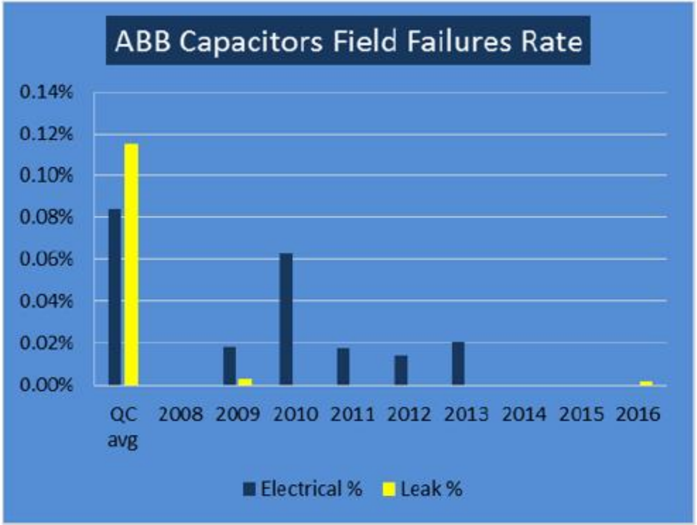


Modern All-Film Power Capacitors Are Quite Reliable

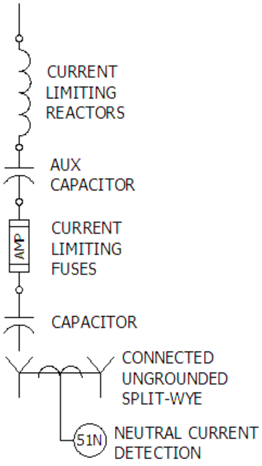
ABB Capacitors - Quebec City

ABB CAPACITORS FIELD FAILURE RATE

Year of MFG	Electrical	Leak	Total
Quebec average			
2002-2008	.08%	0.115%	.195%
China			
2008	0.000%	0.000%	0.000%
2009	0.018%	0.003%	0.021%
2010	0.063%	0.000%	0.063%
2011	0.018%	0.000%	0.018%
2012	0.014%	0.000%	0.014%
2013	0.021%	0.000%	0.021%
2014	0.000%	0.000%	0.000%
2015	0.000%	0.000%	0.000%
2016	0.000%	0.022%	0.022%
avg since 08	0.016%	0.002%	0.018%

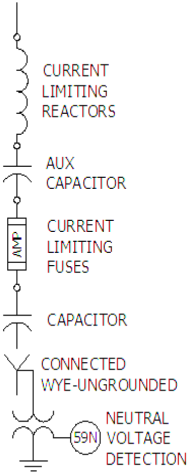


Blown Fuse Detection – Neutral Unbalance Protection



Split-Wye (Double-Wye)
CT in Neutral

(preferred)



Single-Wye
Neutral Voltage Detection

- Covered extensively in IEEE C37.99-2000 – IEEE Guide for the Protection of Shunt Capacitor Banks
- 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

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

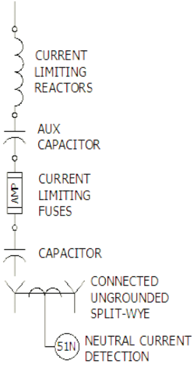
Formulas

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

$$V_{\mathit{REMAINING\ CAPACITOR\ VOLTAGE}} = \frac{V_{\text{Ø}} \times N \times 3}{3N - F} \text{ (VOLTS)}$$

$$V_{\mathit{CAP\ BANK\ NEUTRAL-TO-GROUND}} = \frac{V_{\text{Ø}} \times F}{3N - F} \text{ (VOLTS)}$$

- $I_{\text{CURRENT THROUGH NEUTRAL CT}}$ = Current in amps through CT for one or more capacitor fuse operations
- I_{NOMINAL} = Phase Current of Entire Capacitor Bank (Both Wye-Connected Banks Combined in amps)
- $V_{\text{Ø}}$ = 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.



Split-Wye (Double-Wye) CT in Neutral

(preferred)

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

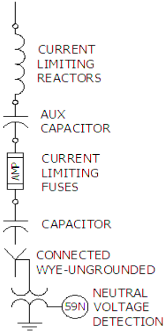
Blown Fuse Detection, Single-Wye (PT In Neutral)

Formulas

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

$$V_{REMAINING\ CAPACITOR\ VOLTAGE} = \frac{V_{\emptyset} \times N \times 3}{3N-F}\ \text{(VOLTS)}$$

- F = Number of Failed Capacitors per Phase
- N = Number of Capacitors per Phase (included on both sides of wye connected capacitor bank)
- $V_{\emptyset}$ = 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.



Single-Wye
Neutral Voltage Detection
(not recommended)

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

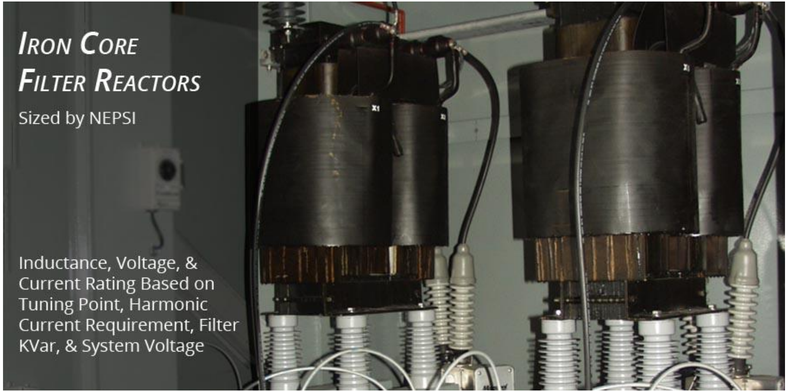
Tuning Reactors

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*



IRON CORE FILTER REACTORS

Sized by NEPSI

Inductance, Voltage, & Current Rating Based on Tuning Point, Harmonic Current Requirement, Filter KVar, & System Voltage

Main Suppliers:

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

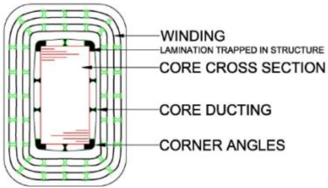
Iron-Core Reactor Suppliers (metal-enclosed filter designs)
Power Magnetics, Control Power Transformer, Hans Van Mangoldt

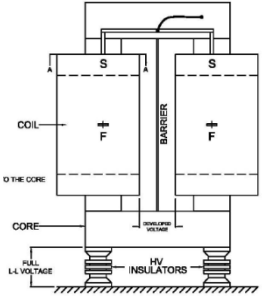
Tuning Reactors, Iron-Core Vs. Air-Core

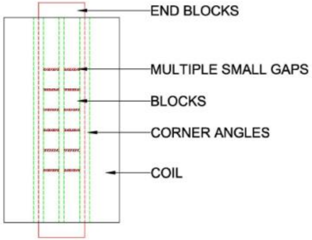
Metal-Enclosed Filter Component

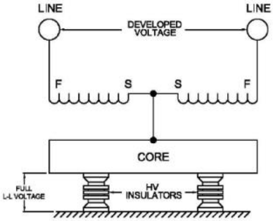
Iron-Core

Single-Phase, Floating Core Design









Open-Air Filter Component

Air-Core

Single-Phase, Floating “Spider” Design

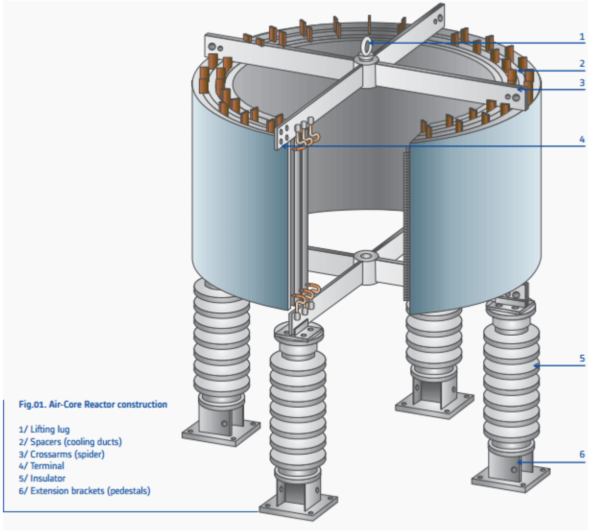


Fig.01. Air-Core Reactor construction

1/ Lifting lug
2/ Spacers (cooling ducts)
3/ Crossarms (spider)
4/ Terminal
5/ Insulator
6/ Extension brackets (pedestals)

Tuning Reactor Options, Iron-Core Vs. Air-Core

Iron-Core

Metal-Enclosed Filter Component

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

Open-Air Filter Component

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

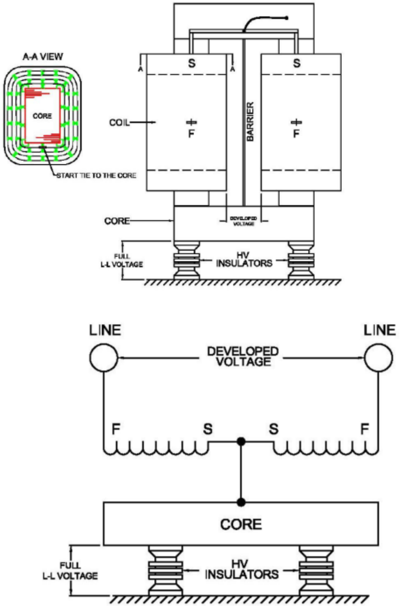
Iron-Core Tuning Reactors

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^2
- 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

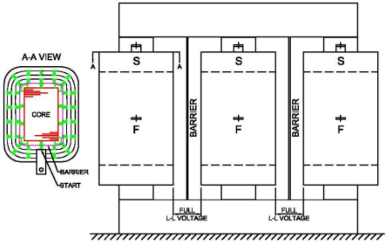
Advantages

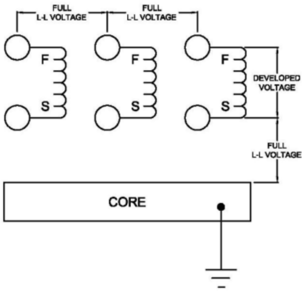
- More available ratings:
  - BIL: 60 to 200kV (max)
  - Filter 3Ø MVAR rating: 0.5 to 18 MVAR (max)
- Low stress design
  - 95% of voltage stress is across HV Insulator
  - 5% voltage stress across winding and winding to core
- Low Noise
- High Reliability

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

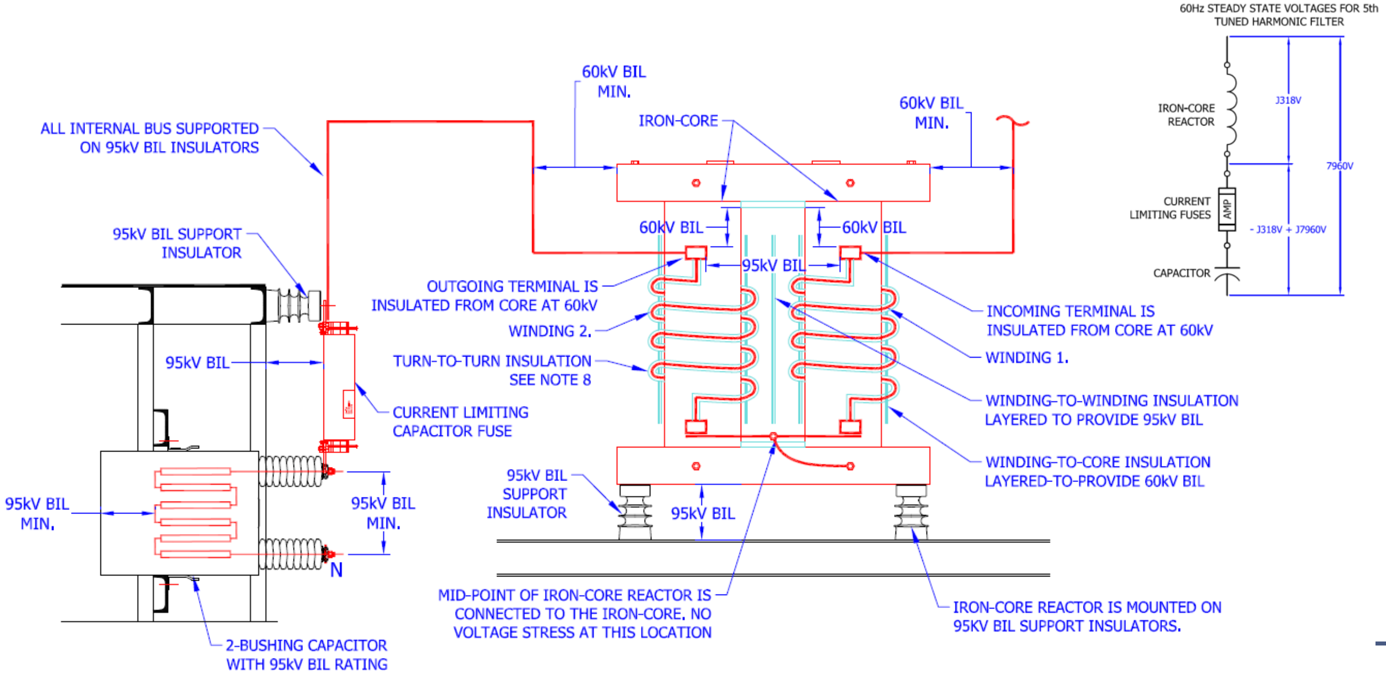
Advantages

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

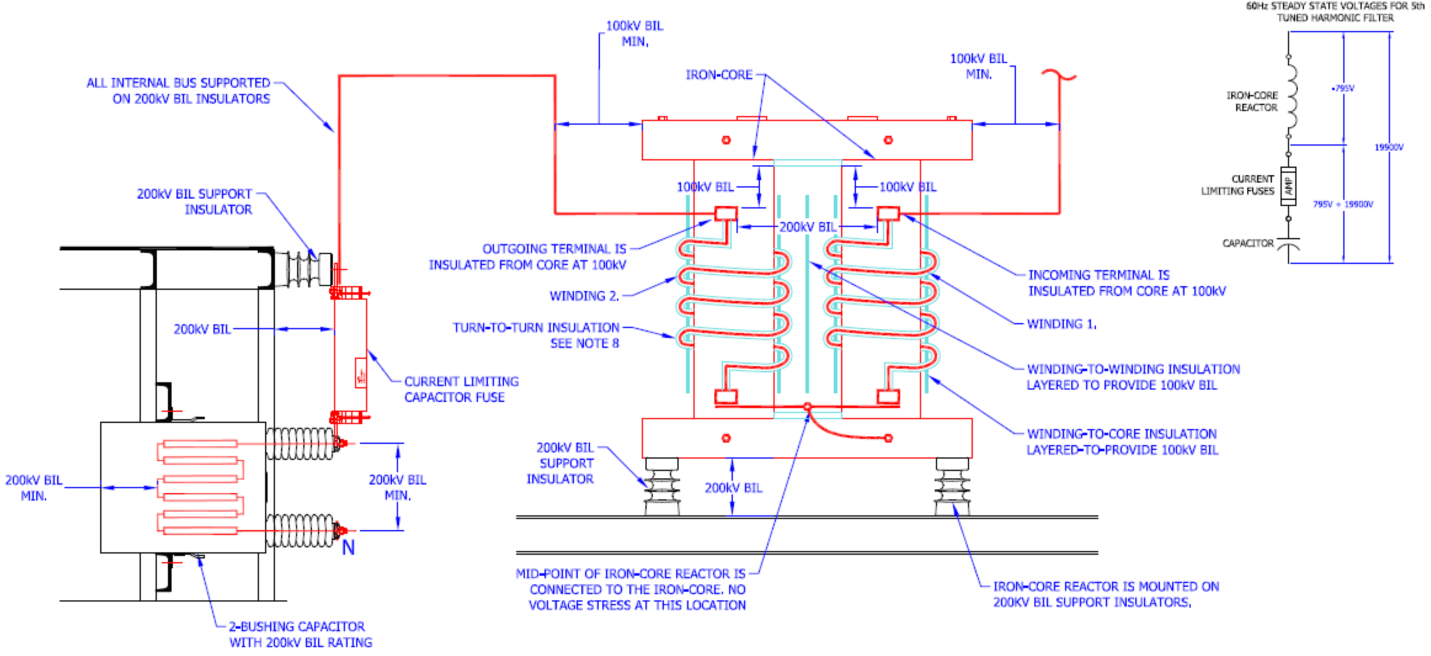
Disadvantages

- 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

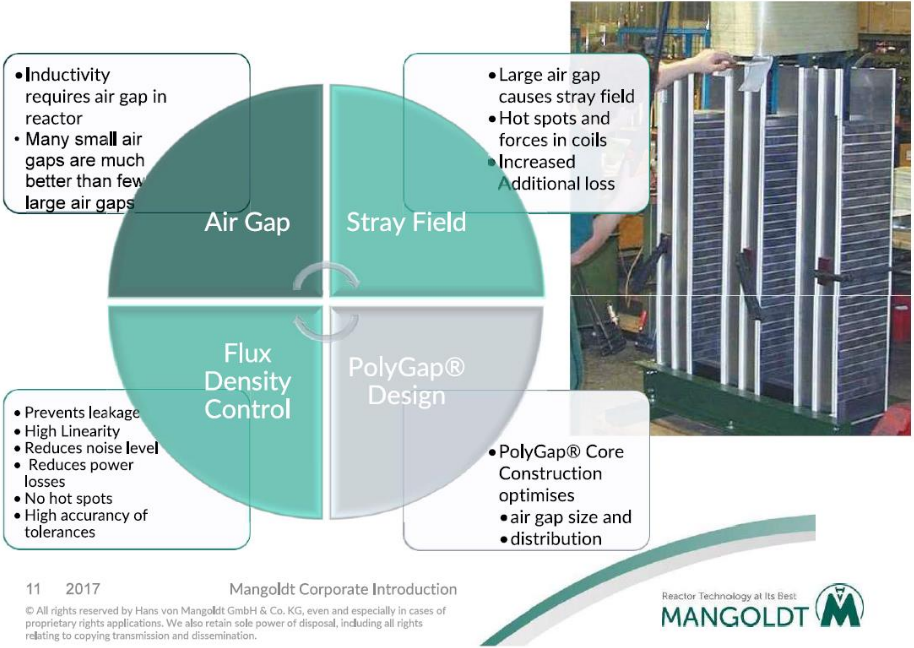
Voltage Stress On 13.8kV Iron-Core Filter Reactor



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

Air Gap

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

Stray Field

Flux Density Control

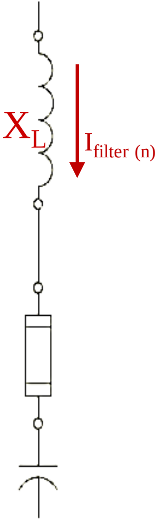
- Prevents leakage
- High Linearity
- Reduces noise level
- Reduces power losses
- No hot spots
- High accurancy of tolerances

PolyGap® Design

- PolyGap® Core Construction optimises
  - air gap size and
  - distribution

11 2017 Mangoldt Corporate Introduction

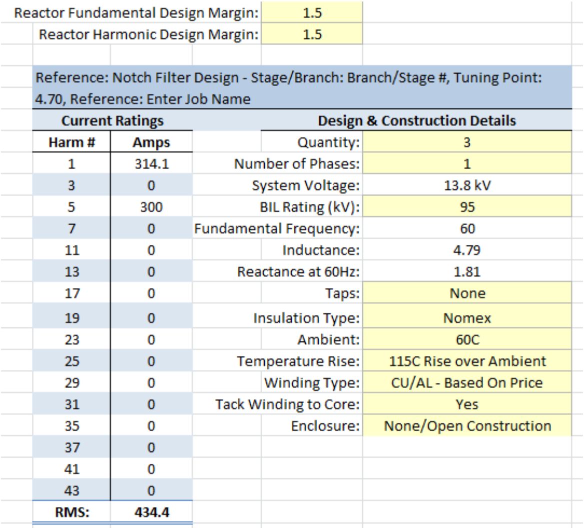
Iron-Core Tuning Reactor Ratings



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 60C for metal-enclosed filters)
- Q Rating (normally very high for iron-core (near 100).

Ratings Table



Reactor Fundamental Design Margin:	1.5
Reactor Harmonic Design Margin:	1.5

Reference: Notch Filter Design - Stage/Branch: Branch/Stage #, Tuning Point: 4.70, Reference: Enter Job Name

Current Ratings		Design & Construction Details	
Harm #	**Amps**	Quantity:	3
1	314.1	Number of Phases:	1
3	0	System Voltage:	13.8 kV
5	300	BIL Rating (kV):	95
7	0	Fundamental Frequency:	60
11	0	Inductance:	4.79
13	0	Reactance at 60Hz:	1.81
17	0	Taps:	None
19	0	Insulation Type:	Nomex
23	0	Ambient:	60C
25	0	Temperature Rise:	115C Rise over Ambient
29	0	Winding Type:	CU/AL - Based On Price
31	0	Tack Winding to Core:	Yes
35	0	Enclosure:	None/Open Construction
37	0		
41	0		
43	0		
RMS:	**434.4**		

Air-Core Reactor Mounting Arrangements

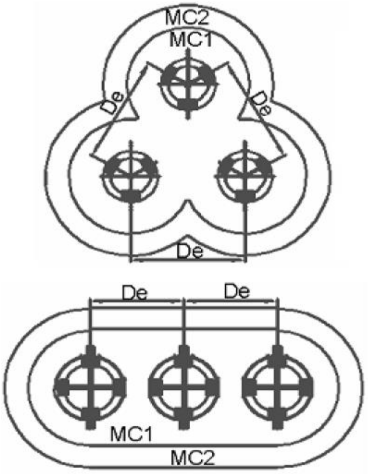
Stacked Reactor Arrangement

Unstacked Reactor Arrangement

Air-Core Reactor – Radial Magnetic Clearance Requirements

Installation Diagram

(magnetic field clearance requirements)



Notes:

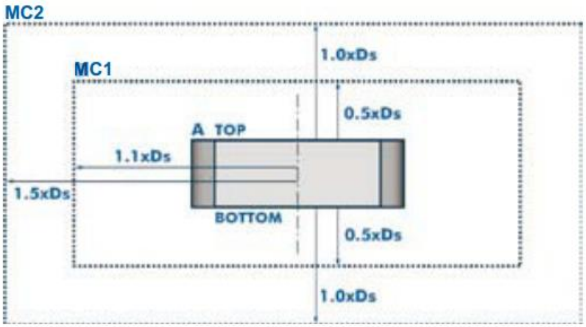
- Stray magnetic fields are significant and can induce currents in metallic parts that may causes thermal and electrodynamic effects. Nearby metal structures, electronics equipment, rebar, etc. shall be located in areas where the effect will not create excessive heating.
- De ≈ 2x coil diameter
- MC1 ≈ 1.1 x coil diameter (metallic parts not forming closed loops – as measured from center of reactor)
- MC2 ≈ 1.5 x coil diameter (metallic parts forming closed loops – as measured from center of reactor)

Air-core tuning reactors have significant footprint requirements

(typical coil diameter: ≈ 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



A: reactor outer surface
Ds: reactor diameter
keep metallic parts not forming closed loops outside MC1
keep metallic parts forming closed loops outside MC2

Notes:

- Sides – Radial Distance
  - MC1 ≈ 1.1 x coil diameter (metallic parts not forming closed loops – as measured from center of reactor)
  - MC2 ≈ 1.5 x coil diameter (metallic parts forming closed loops – as measured from center of reactor)
- Top/Bottom – Axial Distance
  - MC1 ≈ 0.5 x coil diameter (metallic parts not forming closed loops – as measured from center of reactor)
  - MC2 ≈ 1.0 x coil diameter (metallic parts forming closed loops – as measured from center of reactor)

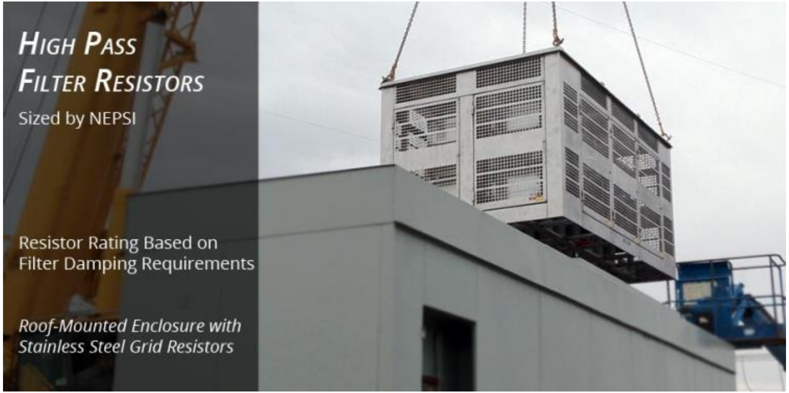
High-Pass Filter Resistors

HP Resistor Standards

- No Standard directly applies
- *IEEE C57.32-2015 - IEEE Standard for Requirements, Terminology, and Test Procedures for Neutral Grounding Devices*

Application Standards –

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

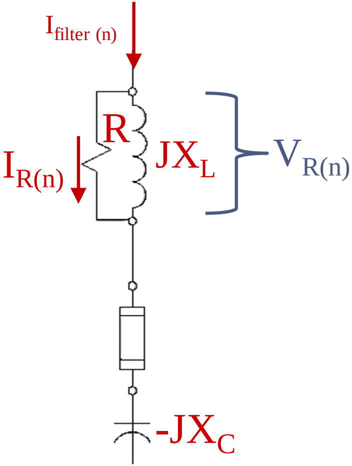


Main Suppliers:
Post Glover, Avtron Power Resistors

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



High-Pass Filter
HP

- 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)

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

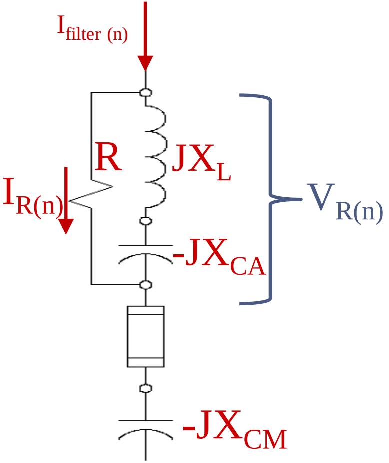
- $I_{R(n)}$ is obtained by dividing $V_{R(n)}/R$ (Amps)
- $I_{Resistor\ RMS\ Current}$ is obtained by taking the square root of the sum of squares of all harmonic currents flowing in resistor

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

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

$$P_{Resistor} = I_{Resistor\ RMS\ CURRENT}{}^2 \times R$$

C-High-Pass (C-HP) Filter Resistor – Rating Calculation



C-High-Pass
C-HP

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

$$V_{R(n)} = I_{filter\ (n)} \times \frac{1}{\sqrt{\frac{1}{R^2} + \left(\frac{1}{\left(X_{L(n)} - X_{C(n)}\right)}\right)^2}} \quad \text{(Volts)}$$

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

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

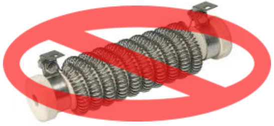
- The single-phase power rating of the resistor is calculated by squaring the RMS current rating of the resistor and multiplying by R.

$$P_{Resistor} = I_{Resistor\ RMS\ CURRENT}{}^2 \times R$$

High-pass Filter Resistor

Typical Stamped Grid Resistor Element

Edge wound and wire wound resistors should be avoided if possible

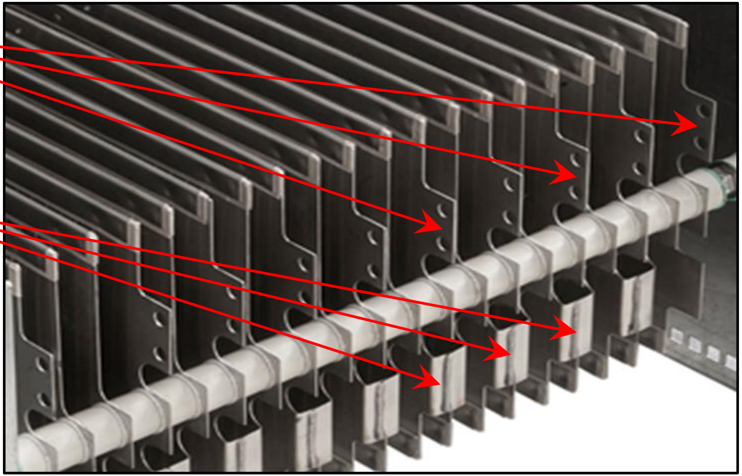


Specify

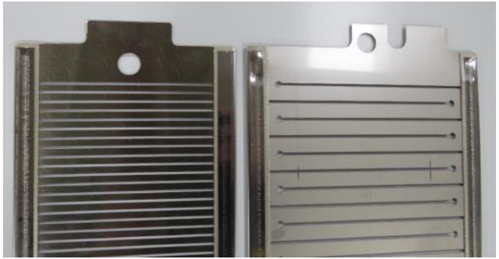
- System Voltage, BIL, Single-Phase Resistance, Elevation, RMS Current Rating of Resistor
- Specify Stainless Steel Stamped Grid Type Resistor Elements
- Cooling: Natural Convection
- Roof-mounted / Rack-mounted in 409/304/316 stainless steel enclosure depending on type of filter
    - Enclosure not 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.

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

Enclosure Features

One-Line

Arc Flash Hazard Mitigation – Design Strategies (cont.)

- **Design Practices that Reduce Probability of Arc Flash Event**
    - Key interlocks
    - Proper choice of capacitor switching device
    - Fuse failure protection
    - Windows
    - Condensation control with heaters
    - Rodent screens/floor
    - Signage
    - Insulated bus bars
    - Increase BIL rating
    - Smoke detectors
    - Partial discharge monitoring
    - Infrared inspection windows

Enclosure Features

One-Line

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