IEEE 519-2014

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What Has Stayed the Same?

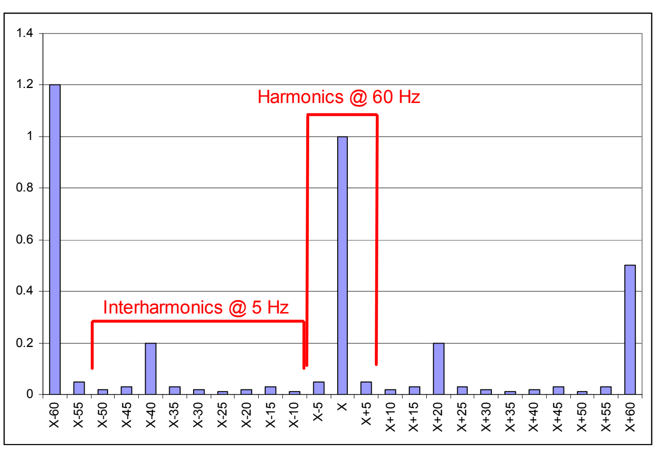
- Most importantly, the overall philosophy
  - Users are responsible for limiting harmonic currents
  - System owner/operator are responsible for managing voltage quality
  - All recommended limits apply only at the PCC
- Existing recommended limits are retained
  - Some new ones added

What Has Been Changed?

- Philosophy of changes → Driven by 20 years of experience with 519-1992 and increased cooperation with IEC
- Multiple changes related to
  - Measurement techniques
  - Time varying harmonic limits
  - Low voltage (<1 kV) harmonic limits
  - Interharmonic limits
  - Notching and TIF/IT limits
- Also "editorial" changes to
  - Reduce document size
  - Minimize miss-use of PCC-based limits
  - Better harmonize with other standards projects

Measurements

- Recommended to use IEC 61000-4-7 specifications
  - 200 ms (12 cycle @ 60 Hz) window gives 5 Hz resolution



Indices

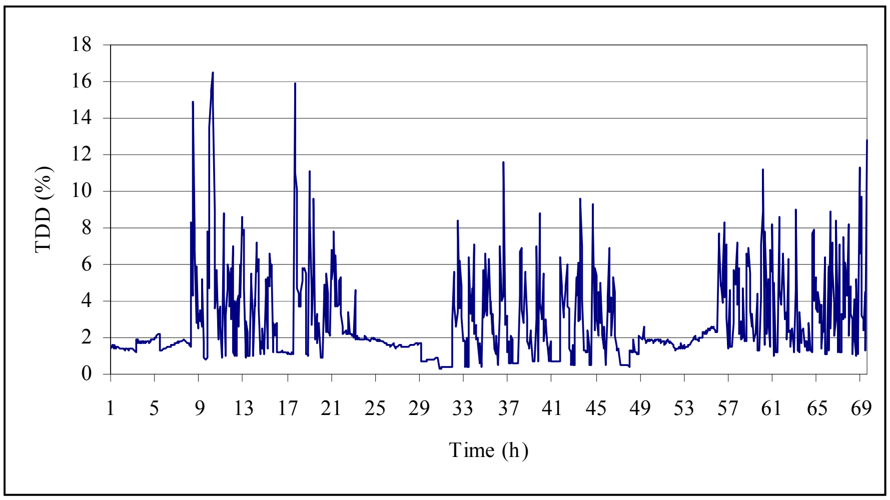
- From IEC 61000-4-30
  - 3 s "very short" value

$$F_{n,vs} = \sqrt[2]{\frac{1}{15}\sum_{i=1}^{15} F_{n,i}^2}$$

  - 10 min "short" value

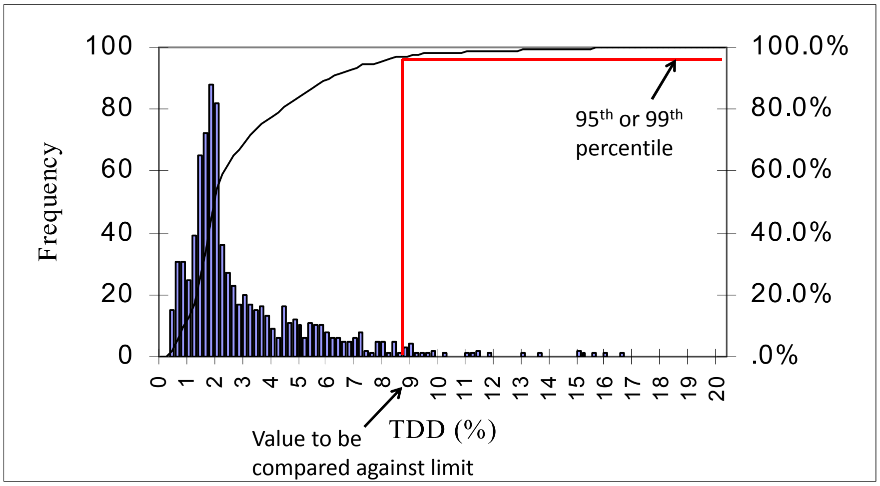
$$F_{n,sh} = \sqrt[2]{\frac{1}{200}\sum_{i=1}^{200} F_{(n,vs),i}^2}$$

Assessment of Limit Compliance



What value should be compared against the limit?

Weekly Statistical Indices



Changes to the Limits

- New voltage limit provision for low voltage (<1 kV)
  - 5% individual harmonic, 8% total harmonic distortion
- Revised current limits for general transmission systems (> 161 kV)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{sc}/I_L	<11	$11\leq h< 17$	$17\leq h< 23$	$23\leq h< 35$	$35\leq h$	TDD
<25*	1.0	0.5	0.38	0.15	0.1	1.5
25<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.5	1.15	0.45	0.22	3.75

Percentile-Based Voltage Limits

- Daily 99th percentile very short time (3 s) values should be less than 1.5 times the values given in Table …
- Weekly 95th percentile short time (10 min) values should be less than the values given in Table …

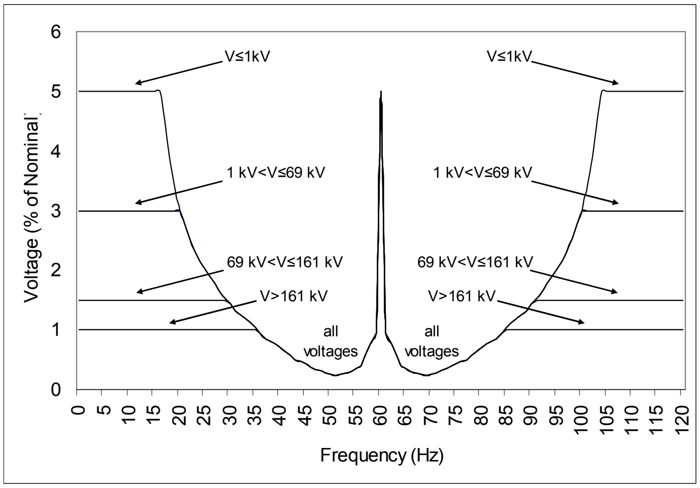
Percentile-Based Current Limits

- Daily 99th percentile very short time (3 s) harmonic currents should be less than 2.0 times the values given in Table …
- Weekly 99th percentile short time (10 min) harmonic currents should be less than 1.5 times the values given in Table …
- Weekly 95th percentile short time (10 min) harmonic currents should be less than the values given in Table …

Interharmonic Limits

("Recommendations")

- Voltage-only 0-120 Hz limits based on flicker



Editorial Changes

- Improve definitions of all relevant terms to account for greater understanding and improved instrumentation
- Removal of "flicker curve"
- Removal of "tutorial" material (shorten document)
- Strengthen introductory material dealing with PCC-only applicability of recommended limits

Experience So Far

- Granted, this is limited mostly to "experiments" over the last 6-12 months
  - Users with relatively stable harmonic emissions are essentially unaffected
  - Users with rapidly-changing harmonic emissions may show reduced levels in measurements
    - The 200 ms window acts as a smoothing filter
- Percentiles and multipliers appear to be relatively consistent with "short time harmonic" multipliers often used with 519-1992

Passive Mitigation of Power System Harmonics

Mark Halpin

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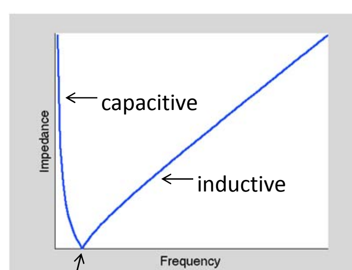
Outline

- Passive Filters
  - Basic resonance concepts
  - Single-tune filters
  - C-type filters
- Performance comparisons
  - Sensitivities to network conditions
  - Overall effectiveness
- Conclusions

Series Resonance Concept

$$\overline{Z}_{eq} = j\left(\omega L - \frac{1}{\omega C}\right)$$
$$= j\left(X_L - X_C\right)$$

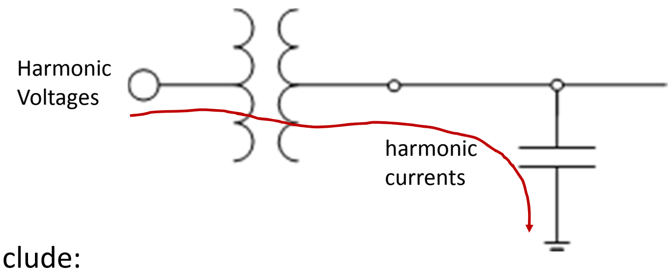


resonant frequency, ω_r

$$\omega_r = \frac{1}{\sqrt{LC}}$$

Major concept: The impedance can become a very low value

Series Resonance In Practice

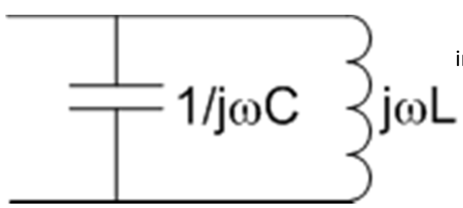


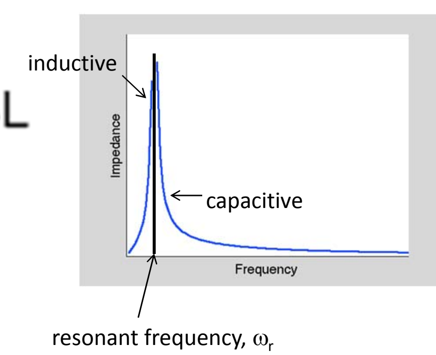
Effects include:

1. Heating in transformer
2. Fuse blowing at capacitor bank

Typical resonances:
--500 kVA, 12.47 kV, 5%
--300-1200 kvar capacitor
--ω_r=173-346 Hz (3^{rd}-6^{th} harmonic)

Parallel Resonance





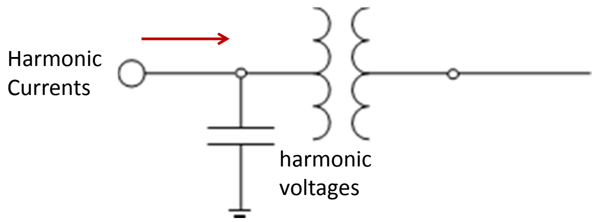
$$\overline{Z}_{eq} = j\omega L \,//\left(\frac{1}{j\omega C}\right)$$

$$= -j\frac{X_L X_C}{(X_L - X_C)}$$

$$\omega_r = \frac{1}{\sqrt{LC}}$$

Major concept: The impedance can become a very high value

Parallel Resonance in Practice



Effects include:

1. Excessive voltage distortion
2. Capacitor bank fuse blowing

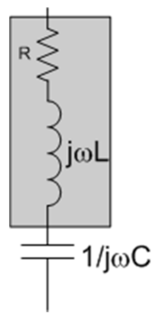
Typical resonances
--500 kVA, 480 V, 5%
--400 kVA load, 80% pf lagging
--pf correction to 95% lagging (120 kvar)
--ω_r=547 Hz (9^{th} harmonic)

Resonance Summary

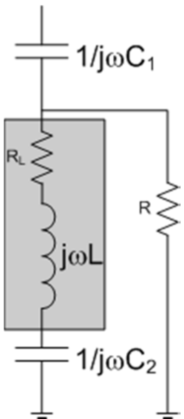
- Series resonance
  - Widely exploited in harmonic filters
  - Can lead to (harmonic) overcurrents
- Parallel resonance
  - Frequently leads to (harmonic) overvoltages
  - Sometimes used in blocking filters

Single-Tuned Filters

- "Single tune" means a single resonant point



Classical Single-Tuned Filter



C-type Filter

Applications

- Classic single-tuned filters
  - Common in industrial applications
    - Inside facility
    - At the PCC
    - May use multiple filters, each tuned to a different frequency
  - Traditionally used by utilities (declining)
- C-type filters
  - Not common in industrial applications
  - Becoming dominant in the utility environment
  - Often used in conjunction with classic single-tuned designs
- Purpose is always the same—give harmonic currents a low-impedance path "to ground"
  - Results in reduced voltage distortion

Application Considerations

- Ratings
  - Capacitor
    - RMS voltage
    - Peak voltage
    - RMS current
    - kVA
  - Reactor currents
    - Peak current
    - RMS current
- Losses

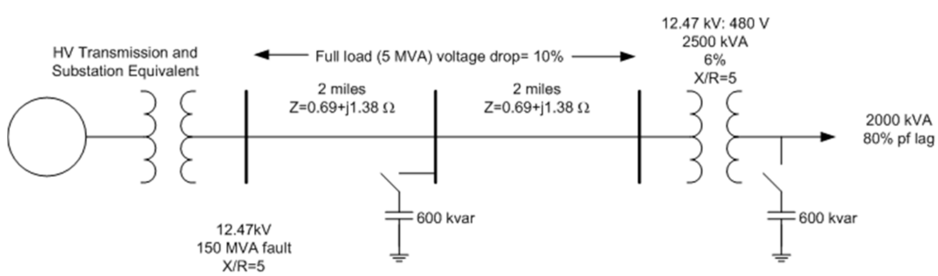
Filter Application Procedure

- Use frequency scan and harmonic study to determine requirements
  - Number of filters (estimate)
  - Tuned frequency for each
  - Ratings (estimate)
- Start with lowest-frequency filter and work upward (in frequency)
  - Each filter has parameters than can be at least partially optimized
  - Consider credible system changes
  - Assess impacts of filter parameter variations (±10%, maybe more)
- Evaluate total performance vs. requirements
  - Consider credible system changes
  - Specify required ratings (tweak design as necessary)

Comments on Frequency Scans

- These results indicate the ***potential*** for a problem
- They are extremely useful for designing filters
  - Identification of high/low impedance frequencies (resonant conditions)
  - Assessment of filter impacts on frequency response
    - Alteration of undesirable impedance characteristics
    - Demonstration of intentional low impedance path(s)
- They are subject to the accuracy of the models used
- Complete assessments require a harmonic study
  - Results subject to model accuracy and assumptions
  - Limit compliance
  - Ratings of components

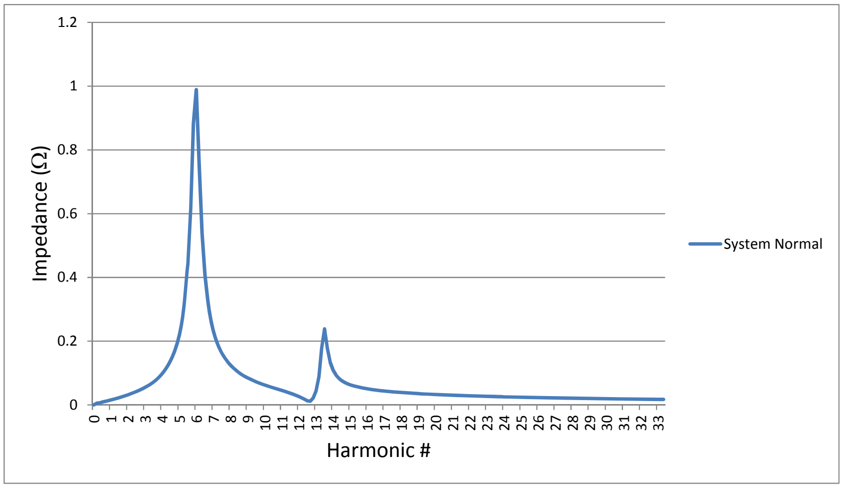
Demonstration Case



- Basic harmonic situation and sensitivities
  - Series and parallel resonance conditions
- Mitigation using filters
  - Single-tuned “industrial”
  - C-type “utility”

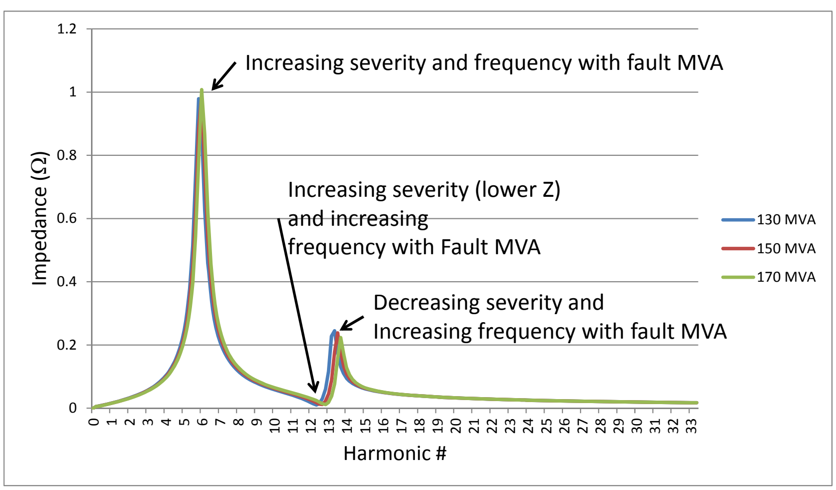
Normal Condition Frequency Response—LV Filter Application

(Are impedances high or low at known harmonic frequencies?)



Sensitivities—Substation SC Power

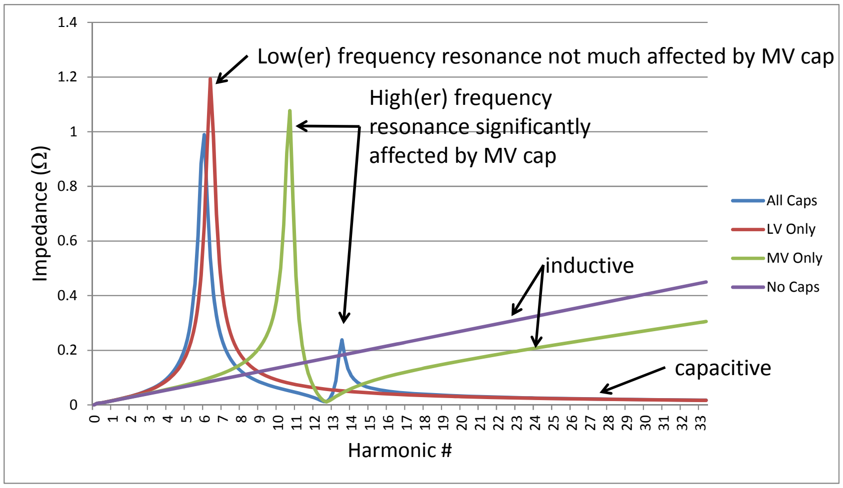
(equivalent impedance at LV bus)



These sensitivities would be considered pretty small and insignificant

Sensitivities—Capacitor Status

(equivalent impedance at LV bus)



Low(er) frequency resonances not much affected by things that impact high(er) frequency response—opposite not true!!

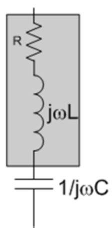
Sensitivities--Conclusions

- Large changes in system impedances, equivalents, etc., (fault MVA) are usually needed for significant effects
- Relatively small changes in capacitor bank status (or size) can have major impacts
- Filters must function under all of the potential scenarios

Design Approach

- Convert existing 480 V cap bank to filter bank by adding series reactor
  - Capacitor voltage rating often will be exceeded in the end!
  - X/R ratio of reactor can have significant impact
    - Losses
    - Performance
  - Additional resistance can be added in series if needed (losses will increase!) for performance

Note: Tuned frequency normally taken ≈5% below target
→Avoid overload
→Parameter variation



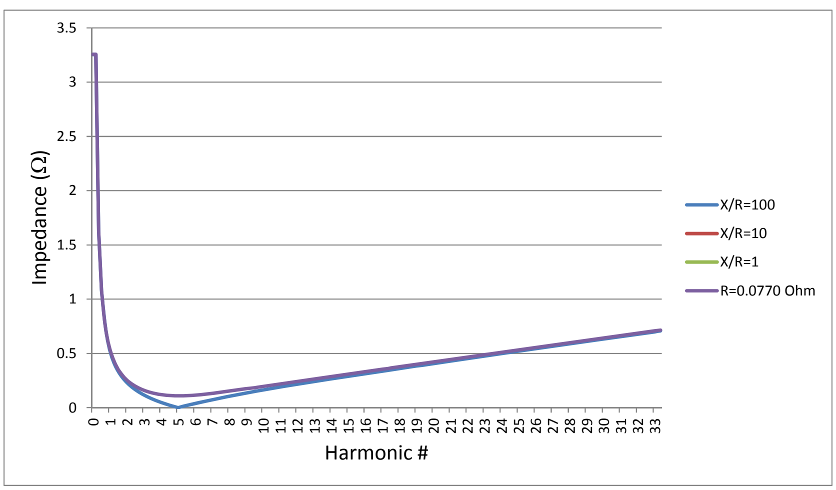
$$f_{tune} = \frac{1}{2\pi\sqrt{LC}}$$

$$300 = \frac{1}{2\pi\sqrt{L(.006908)}}$$

$$L = 40.7\mu H$$

$$X_L = 15.4 m\Omega$$

5th Harmonic Single-Tune Design



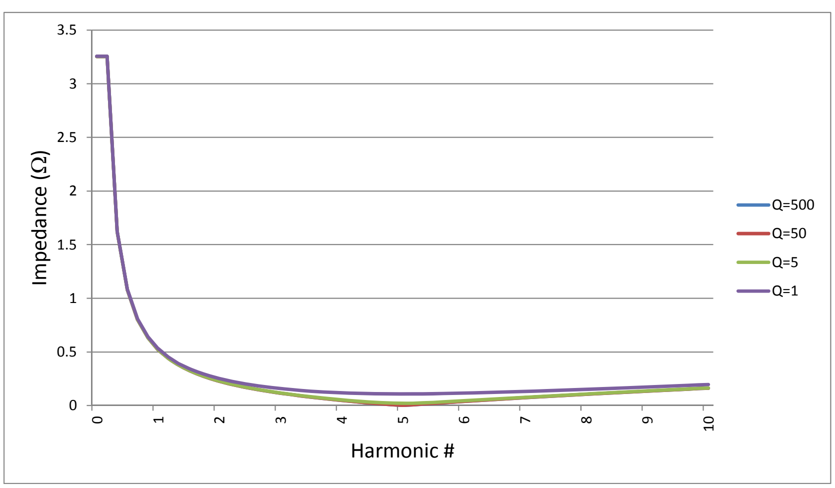
Filter Quality ("Q") Factor

- The "sharpness" of the frequency response of a filter is often indicated by the filter "Q"

$$Q = \frac{h_{tune} X_{L(60)}}{R} = \frac{(2\pi f_{tune})L}{R}$$

- The filter Q indicates
  - Damping (less sharp characteristic—more damped)
    - Lower Q, more damping
  - Losses
    - Lower Q, more losses
- For the previous slide
  - Q=500, 50, 5, 1

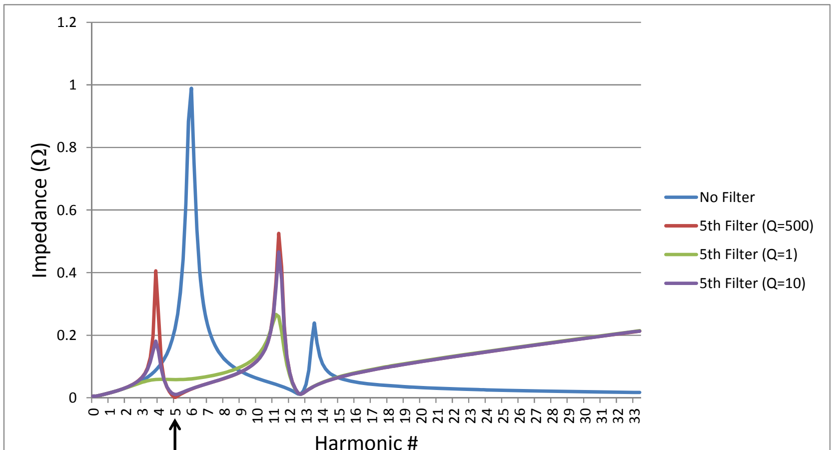
A Closer Look at Q



All this discussion of Q doesn't look like a big deal…

Performance Evaluation

(480 V Bus Impedance)

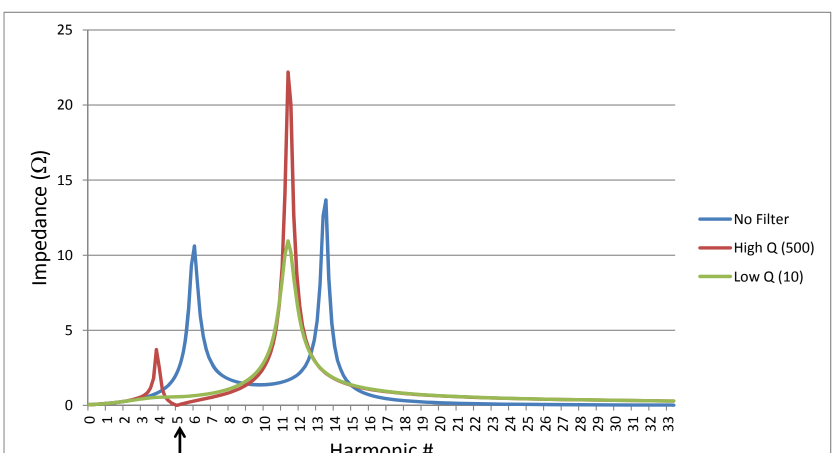


5th harmonic currents produce much less 5th voltage after filter

Filter Q has an obvious impact on the entire response!

Performance Evaluation

(LV Filter Impact on MV System at Cap Bank)



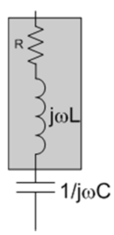
5th harmonic currents produce much less 5th voltage after filter

Lower Q: Not as much filtering at 5th harmonic much less amplification at higher frequencies

Filtering on 12 kV Network

- Discussion so far based on filtering on customer-side (LV)
  - Presumably associated with limit compliance
- If all network users are in compliance (currents), excessive voltage distortion may still exist
  - Strong resonances can create large (noncompliant)voltage effects from small (within compliance) currents
  - Solution is to filter on MV (utility) side
  - Filter designs must account for LV filter presence (or not)

Same Approach for Filter Design



$$f_{tune} = \frac{1}{2\pi\sqrt{LC}}$$

$$300 = \frac{1}{2\pi\sqrt{L(10.235\mu)}}$$

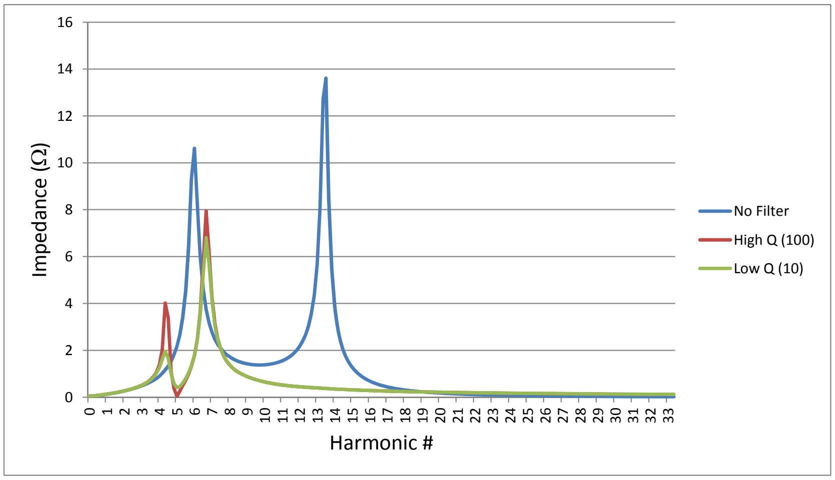
$$L = 27.5\text{mH}$$

$$X_L = 10.367\Omega$$

Note: Tuned frequency normally taken ≈5% below target
→Avoid overload
→Parameter variation

Q=100→R=0.5184 Ω
Q=10→R=5.1835 Ω

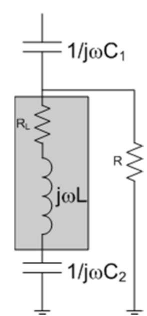
12 kV Filter Performance



Filter eliminates 5th resonance, but creates new ones that could be as bad (or worse).
Best solution probably to split 600 kvar into 2x300 kvar and make two filters—5th and 7th

The C-type Filter

- Tuning (selection of parameters) is more difficult than for single tuned filters
- Starting from an existing cap bank C_{total}
  - Step 1→ Choose L to tune filter frequency as for single-tuned designs (based on C_{total})
  - Step 2→ Divide existing capacitance into two parts
    - C_2→ chosen so that L and C_2 are series resonant (Z=0) at the power frequency
    - C_1→ determined from "C_{total}-C_2" (C in series combines as parallel)
  - Step 3→ Pick R to provide desired high(er) frequency damping

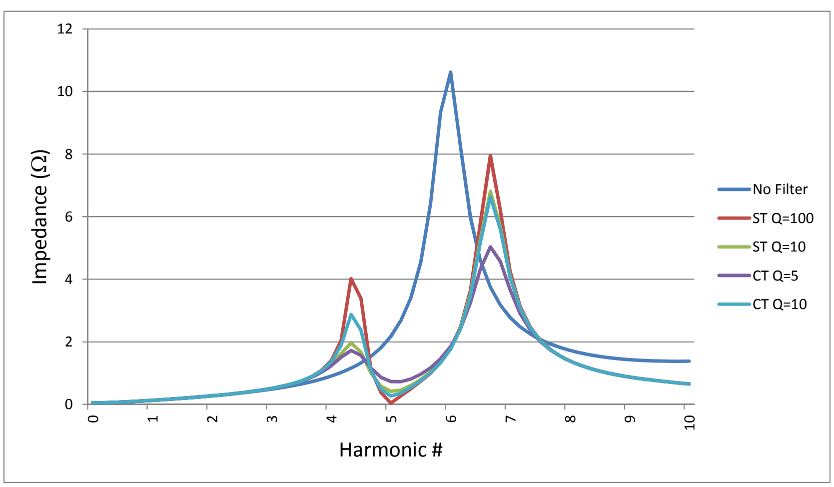


C-type Filter Example

- Will a 12 kV C-type perform better than the conventional single-tuned design?
- Existing 600 kvar bank→C_{total}=10.235μF
  - L=10.367 Ω (27.5 mH) for f_{tune}=300 Hz (from ST design)
  - For 60 Hz "bypass" tuning, C_2=255.85 μF
    - C_1=10.66 μF
  - Select R for desired damping
    - Note Q defined differently

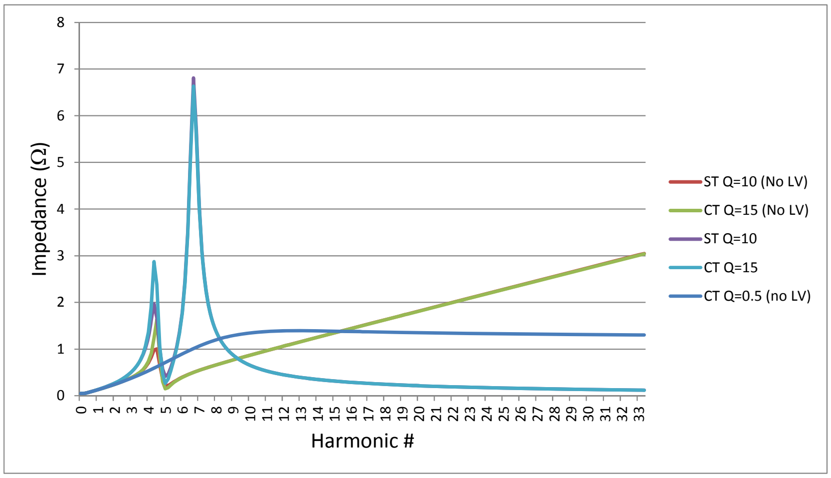
$$Q = \frac{R}{h_{tune} X_{L(60)}} = \frac{R}{(2\pi f_{tune})L}$$

C-type vs. ST Filter Performance



12 kV Filter Sensitivities

(LV Cap/Filter Off-line)



The real advantage of the C-type is control of HF response

Comments on Comparisons

- Both filter types are effective at the tuned frequency
- C-type has very low power frequency losses
  - Single-tuned filter has resistive losses proportional to cap bank reactive current squared
- Low Q single tuned designs are helpful to reduce secondary resonances created by filter additions
  - Alternative is to add secondary filters
- Low Q C-type designs provide good damping of secondary resonances by default
  - Much less likely to encounter “secondary” problems
- C-type designs make poor utilization of existing cap banks
  - Consider using one bank for var compensation with a separate filter installation

Passive Filter Conclusions

- Two main types exist—both work
  - Single tuned
    - Main advantages: Simplicity, up-front cost
    - Main disadvantages: losses, can create secondary problems
  - C-type
    - Main advantages: Low losses, HF response
    - Main disadvantage: up-front cost, poor utilization of existing cap banks
- Frequency scans are a great tool for filter design
  - A harmonic study is required to determine necessary ratings