EASYPOWER WEBINAR

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Harmonic Notch Filters

1.0 Introduction

Harmonic notch filters are one method to mitigate harmonic distortion conditions and/or avoid harmonic resonance when applying power factor correction capacitor banks.

For this webinar, we will focus on notch filter application as it is one of the most common harmonic filter types used. EasyPower has 4 filter types, but the notch is the most predominant in the industry. Notch filters have the structure shown in Figure 1. They include power factor correction as a natural function since they include a sizeable three-phase capacitor bank paired with a set of tuning reactors.

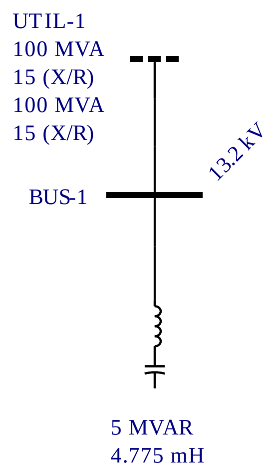

Figure 1. Notch filter in EasyPower.

The database dialog for the notch filter is shown in Figure 2. As just noted, we have data entry for a series inductor set as well as a shunt connected capacitor bank. Since the harmonics routine in EasyPower is predominantly positive sequence (i.e. a balanced simulation), the series inductors are considered to be one per phase for a three-phase filter, and the capacitor bank is considered to be a three-phase bank connected either wye-ungrounded or delta. This arrangement is shown in Figure 3.

The main goal in notch filter application is to tune the notch filter to the lowest problematic harmonic (typically the 5^{th} harmonic for most industrial systems) so that the filter shunts off the harmonic current and keeps it from increasing voltage distortion as it exits a facility through the upstream impedance (typically a plant supply transformer). The filter present a "low impedance" to system at the point it is connected so that currents of a defined frequency choose to flow into the filter instead of the network via current division.

A key secondary goal is sizing the capacitor bank to achieve a desired amount of power factor correction. Typically, this is done first, as the tuning reactor reactive impedance will need to be specified to generate the desired harmonic tuning. The var loss in the reactors is typically minimal, so once the PF correction is decided upon, it should be good. Note however that with harmonic filters, we typically increase the voltage rating of capacitor units to handle the increased peak voltage stress due to absorbing harmonic current. The kVar output will drop by the square of the voltage ratio (applied voltage vs. rated voltage) since the capacitor bank is simply a passive capacitive reactance. This must be considered when sizing the capacitor bank. A good formula to use is shown here:

$$\text{kVar Output} = \left(\frac{kV_{LL\ Applied}}{kV_{LL\ Rated}} \right)^2 \cdot \text{kVar Rated}$$

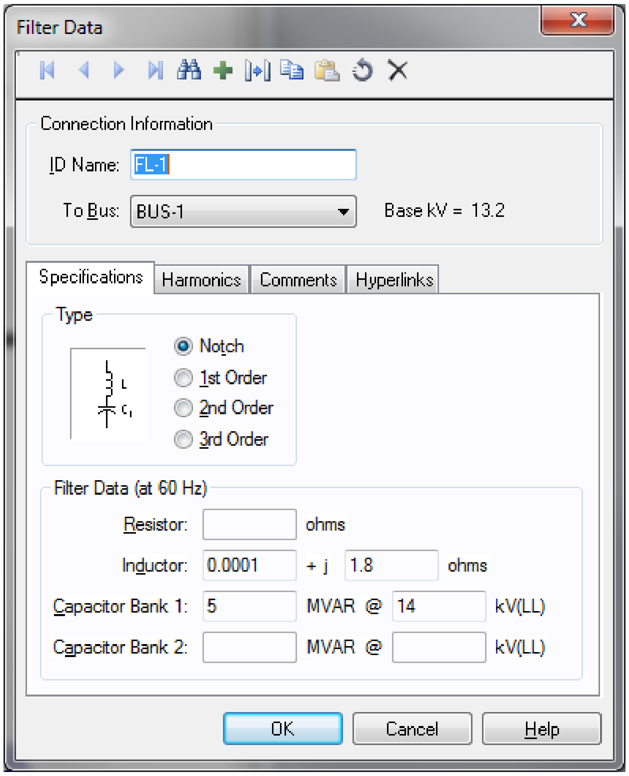

Figure 2. Filter data dialog in EasyPower.

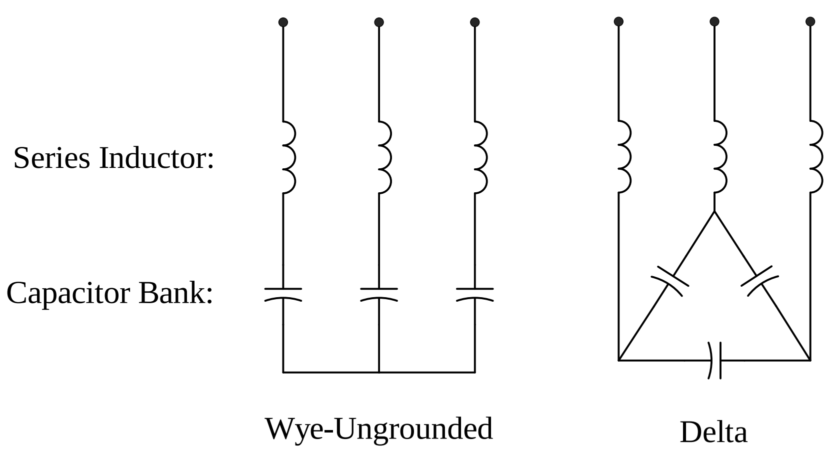

Figure 3. Notch filter arrangements simulated.

EasyPower automatically simulates a capacitor bank in this way, and so when you enter the rated kV for the bank, you will get the kVar out of the bank base on the ratio of applied voltage to rated voltage. The power flow simulation also includes all of the system settings (transformer taps, loading, voltage drops, etc.) so that the vars shown on the oneline represent the actual condition as modeled.

2.0 Impedance Buffering

To minimize the interaction of installed filters with equipment and harmonic producers of other facilities, buffering impedance is necessary. This impedance in essence de-tunes the filter from the perspective of other loads. The most common buffering impedance used is that inherent within supply transformers.

Impedance Buffering minimizes interaction of a harmonic filter with other parts of the electrical power system.

As seen in Figure 4 below and in EasyPower case ResonanceEffect.dez, each unit substation has its own 5 MVar 5th harmonic filter. A couple of other smaller 5th harmonic filters are shown on the left side sub for some class options, but let's focus on the two 5 MVar 5th filters. These filters will interact with each other. For current injected at one unit sub bus, it has to work through the buffering impedance and then back down through the unit sub two buffering impedance. In most cases, the utility impedance is significantly less than the transformer impedance, and currents will seek the lower utility impedance.

There is a natural filter as viewed from the 115 kV bus through each transformer buffer and then the actual filter reactance and capacitance. The de-tuning effect of the additional buffer impedance causes the 115 kV to see less difference from a pure reactance than one would see on the 13.2 kV bus. Frequency response (scan) plots for injections at the unit sub bus and the utility bus are also supplied in Figure 4.

Filtering using any form of tuned harmonic filter necessitates buffering. Buffering minimizes interaction of a harmonic filter with other parts of the electrical power system where we really do not desire to filter. We will have to specify ratings of the filter, and thus its application is dependent upon its interaction with the "nearby" electrical system.

3.0 Capacitor Duty

The capacitor units in a filter design need to be specified properly according to their applied voltage stress and their desired vars as a power factor correction unit. Filters will supply almost the same amount of rated kVar as there would be in a straight shunt capacitor bank installation. This is due to the volt rise in the reactor causing an increase in the capacitor units var output. There are numerous options that are available to us, but the most common kVar and voltage ratings are typically applied.

The limits listed are the absolute maximums. Discussions with a manufacturer's engineer involved with Standard 18 have led to a more conservative approach on the % Rated Crest Voltage. That approach is that if the peak voltage stress under abnormal conditions is within 120% of rating, and under normal conditions is within 100% of rating, then we have a conservative design. This is the approach recommended, as capacitor units have one of the highest failure rates of any electrical equipment. The film-foil design (very thin mylar dielectric film and aluminum foil) is easily damaged by transient and steady-state over-voltage, and thus to extend life of capacitors, exposing them to a peak voltage stress at or below rated voltage is the best approach.

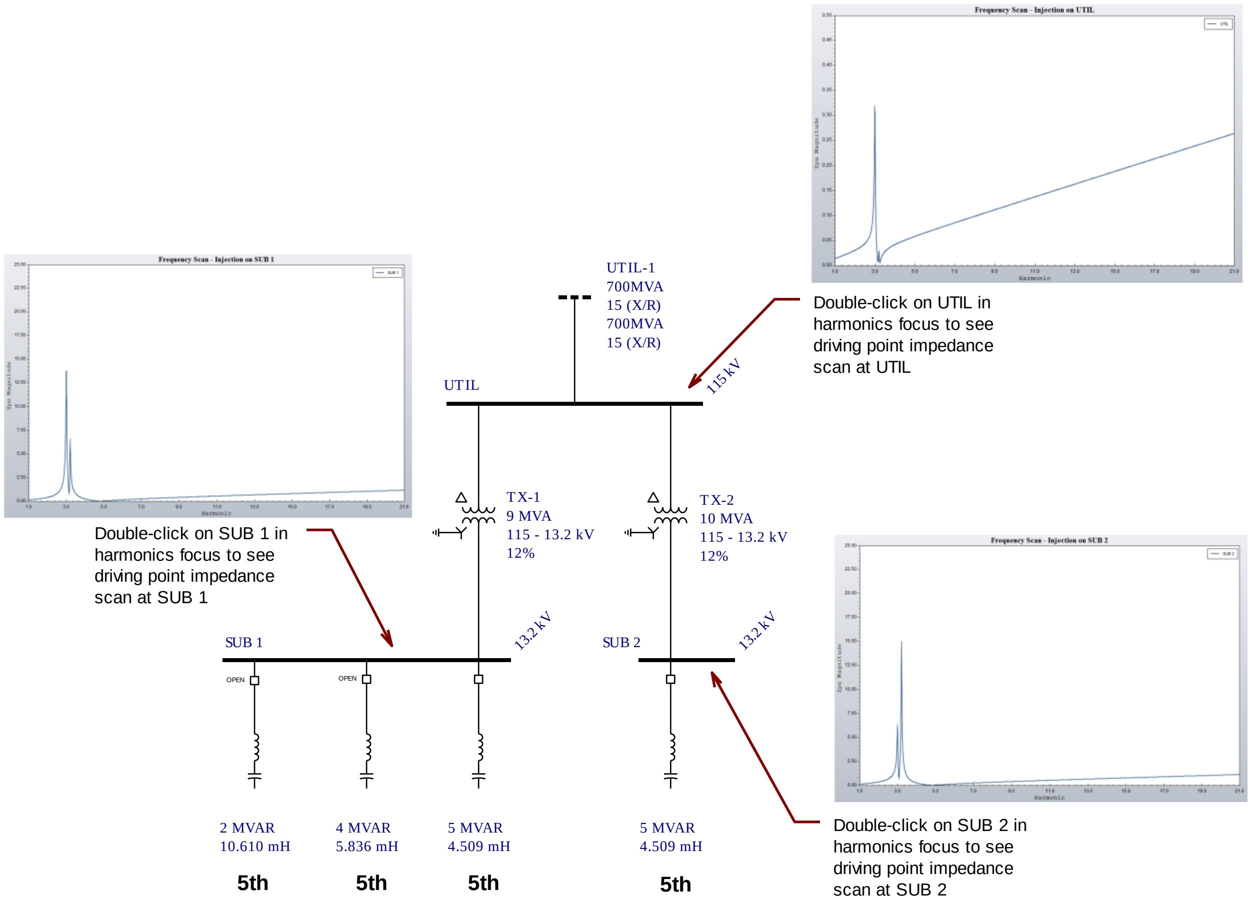

Figure 4. Effect of buffering impedance on driving point impedance.

According to ANSI Standard 18, the following criteria are used to properly rate a capacitor:

Criteria	Limit	Comment
% RMS Amps	135	Use I RSS from harmonic analysis
% Fund kVar	135	Use kVar from PF results
% Rated Voltage	110	Use V RSS from harmonic analysis
% Rated Crest Voltage	120	Use VSUM from harmonic analysis

Here are a few more definitions for our capacitor application:

VSUM. V_{Sum} is used to determine the peak voltage stress on a capacitor unit. V_{Sum} is the linear sum of RMS voltages to generate an estimate of peak voltage. Its formula is:

$$V_{Sum} = \sum_{h=1}^{N} V_h$$

VRSS. V_{RSS} or the "root sum square" voltage, is calculated using individual harmonic components of a decomposed waveform. If every harmonic component that was originally included in the input wave shape is included in this sum of squares, it is identically equal to V_{RMS}.

$$V_{RSS} = \sqrt{V_{DC}^2 + V_1^2 + V_2^2 + V_3^2 + V_4^2 + V_5^2 + V_6^2 + ... + V_N^2}$$

VRMS. V_{RMS} or the "root mean square" voltage, is defined in integral form as:

$$V_{RMS} = \sqrt{\frac{1}{T}\int_0^T v(t)^2\,dt}$$

However, this form relies on knowledge of the actual time wave shape in terms of mathematical equations. The discrete form of the equation is a bit more useful. We can simply represent the waveform via digitized data points (v_n) instead of a deterministic signal (equation) with mathematical terms. By applying an Euler integration technique and noticing that the accumulated Δts become T and cancel we get:

$$V_{RMS} = \sqrt{\frac{\sum_{n=1}^{N} v_n^2}{N}}$$

Unit kVar Rating. 50, 100, 150, 200, 300 or 400 kVar units are standard though any custom order rating can be specified within reason.

Unit Voltage Rating. There are many standard voltage ratings for medium voltage capacitors, but as with kVar rating, any custom order voltage rating can be specified. Low voltage capacitors are almost always rated the standard 600 V.

4.0 First Parallel Resonant Point

Each filter applied on a bus will create a parallel resonant condition below the tuning point. Where the resonant point is depends on the bank size, the utility system impedance, and harmonic at which the filtering point is tuned. In all cases of design, this parallel point must be checked and verified that it does not lie directly on top of an integer harmonic. For example, a 5^{th} harmonic filter will most likely be tuned to filter around the 4.7^{th} to 4.9^{th} harmonic. The 1^{st} parallel resonant point must not peak directly on the 2^{nd}, 3^{rd}, or 4^{th} harmonic. 2^{nd} harmonic is produced during transformer inrush. There could be residual 3^{rd} produced by the harmonic load. The 4^{th} harmonic for some unexplained reason has caused feedback problems in drive and rectifier controls. Try to position the 1^{st} parallel resonant point directly between two integer harmonics.

Table 1. Typical Capacitor Unit Voltage Ratings and BIL.

Unit Voltage	BIL
2400	75
2770	75
4160	75
4800	75
6640	95
7200	95
7620	95
7960	95
8320	95
8760	95
9540	95
9960	95
11400	95
12470	95
13280	125
13800	125
14400	125
15125	125
19920	125
21600	125

5.0 Slightly De-tuned Filters

Harmonic filters are typically de-tuned slightly below the harmonic that needs to be filtered. This is done so that if the bank loses a single or more (depending on filter size and design) capacitor unit, the filter will not move its 1st parallel resonant point up into the harmonic that should be filtered. If such a condition were to happen, then a slight resonance could cause additional units to blow fuses, again moving the 1st parallel resonant point higher, and thus cascade the entire unit into failure as the resonance peaks.

Most filters, depending upon the number of capacitor units, will be designed with protective circuits so that a single loss of a unit (very likely) will alarm, and a loss of two units on a single phase will trip the entire bank. The most common form of blown capacitor protection is a neutral offset detection on the ungrounded wye neutral. When a single unit blows on a phase, the neutral will offset a known amount. For two units blown on a single phase, the neutral will offset past the trip characteristic.

Some older filters were tuned directly on the harmonic needing to be filtered. These designs relied on the inherent positive tolerance within capacitor units to de-tune the unit. Capacitors typically will have a +3 to +5% tolerance in the actual kVar rating. The additional kVars will push the filter point lower. This technique does not coordinate well with blown can protection. For such in-service filters, if the filter reactors have taps, it is recommended that they be considered for tap adjustment after the filter tuning point is verified.

6.0 Bank kVar Size vs. Filter Point Width

As the kVar size of a filter increases, its filter point will broaden. This is especially useful when we de-tune the filter slightly to avoid resonance issues on blown units. As the following figure shows, a simple system with single supply transformer and filter on a 480 V bus, the filter point broadens greatly and the 1st parallel resonant point is pushed down for larger bank sizes. For a small bank, the first parallel resonant point is dangerously close to the filter point and filter effective absorption is restricted.

When several filters, i.e. 3rd, 5th, 7th, are applied together and the total reactive kVar needed is distributed among the filters for proper power factor correction, the effectiveness of each filter is reduced. This is one reason why larger, lumped, single tuned filters are used more often than an entire array of smaller filters at various tuning points. Also, the cost of one set of reactors is less expensive that several sets of reactors.

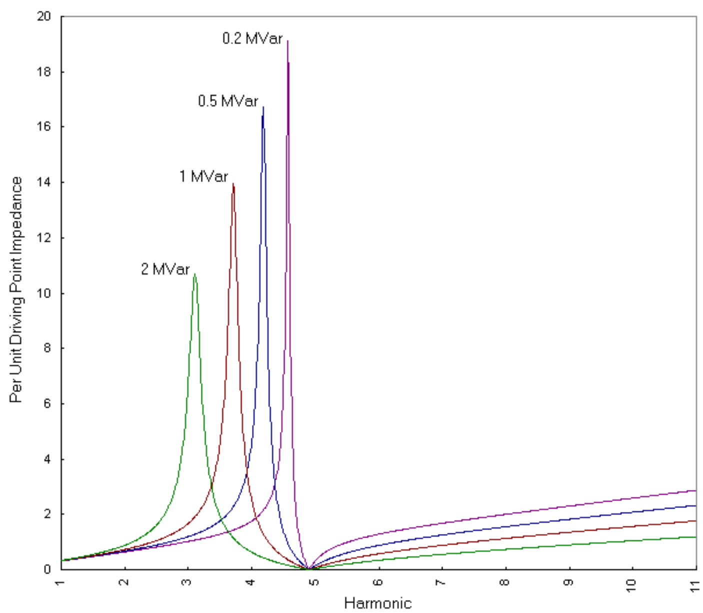

Figure 5. Driving point impedance at increasing capacitor bank sizes.

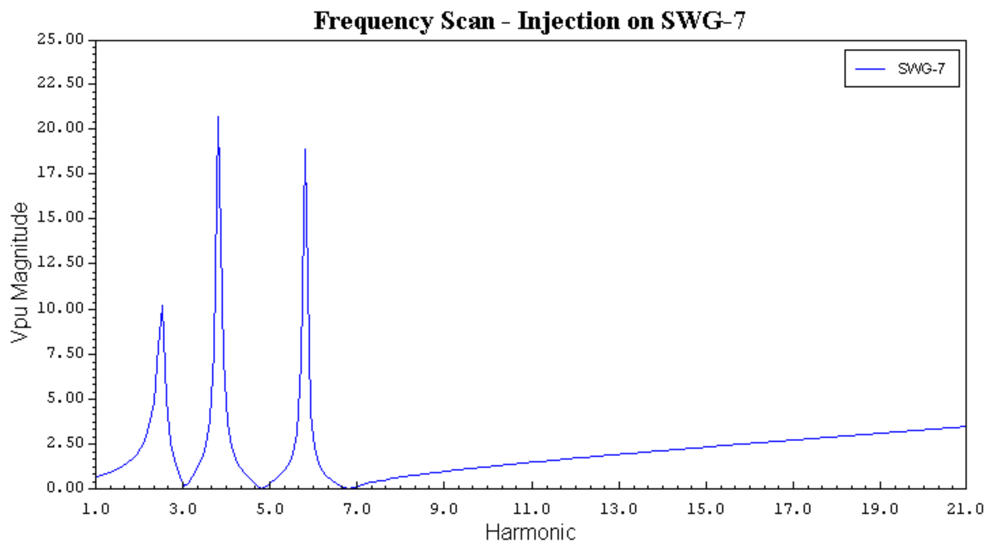

Figure 6. Driving point impedance of multi-stage bank.

7.0 "Identical" Filters on a Single Bus

If multiple filters that are supposedly identical are connected on the same bus, there is the potential that the filters will inter-resonate on a problem harmonic. As seen in the figure below, if a bank has a blown unit and has its tuning point just above the 5th, and a second "identical" filter on the same bus does not have the blown unit and is tuned just below the 5th, then resonance will occur on the 5th. Remember, due to tolerances, no two filters are identical even though they were originally intended to be.

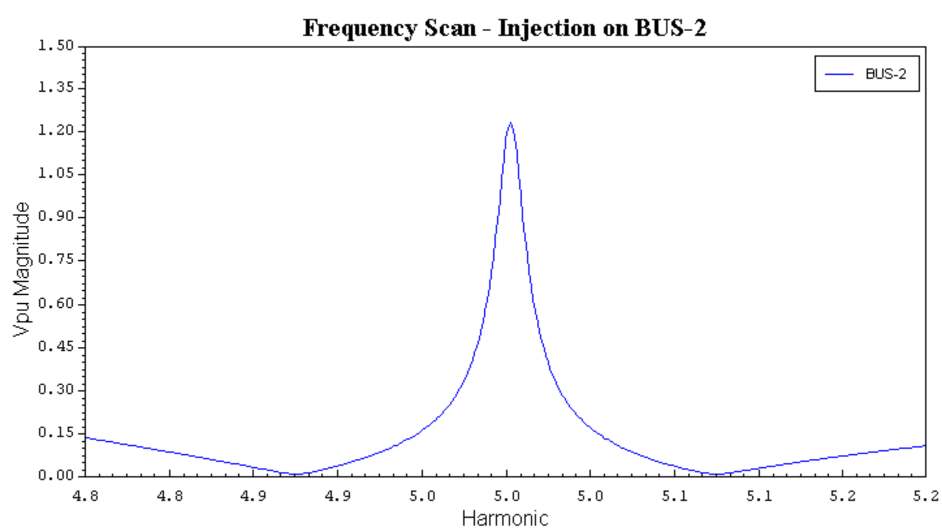

Figure 7. Inter-filter resonance.

8.0 Mixing Filters and Bare Capacitor Banks

Harmonic filters should not be mixed with bare capacitor banks. As can be seen in the figure below for a simple system with a supply transformer, .5 MVar 5th harmonic filter and a 0.5 MVar bare bank, the filter has no effect on changing the resonant condition of the bare capacitor bank at all. It will still exist and cause problems.

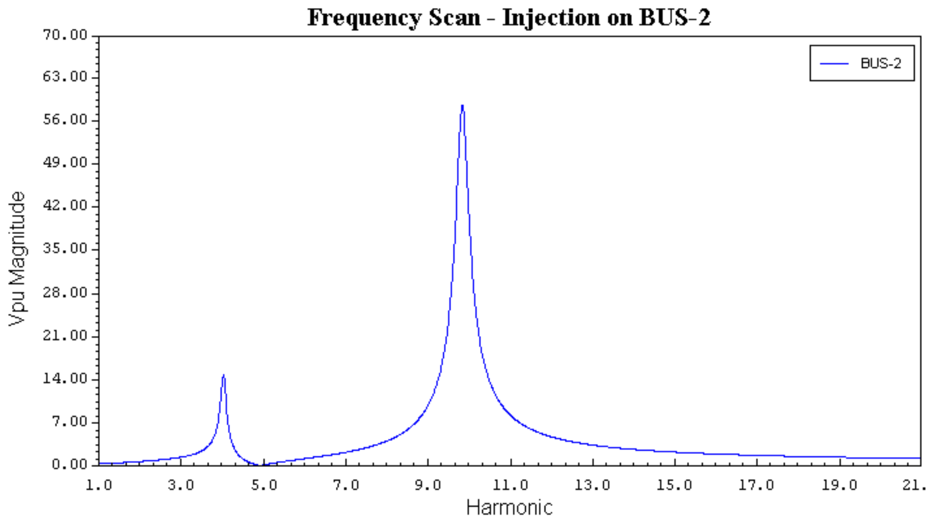

Figure 8. Resonance with filter and bare capacitor.

9.0 Filter Ability to Absorb Higher Harmonics

Harmonic filters, due to their impedance characteristic vs. the system impedance, will typically absorb additional higher frequency harmonics. Harmonic currents choose their path of current flow according to current division. If a 5th harmonic filter still presents a lower path than the utility, then 7th harmonic currents will divide with a greater portion favoring the filter. This is why we include all harmonics in the design of our filter, and not just the 5th alone. The filter needs to be rated according to all harmonics that it will absorb during operation. Additionally absorbed harmonics also have an affect on capacitor unit peak voltage stress.

10.0 Series and Parallel Capacitor Bank Arrangements

For all medium voltage applications, capacitor units will be connected in parallel. Unit voltage ratings (see table of typical voltage ratings above) are adequate so that no series combinations are necessary. For higher voltage filters, on a 115 kV system for example, series arrangements will be necessary so that applied voltage is within ratings of each capacitor unit.

11.0 Rating the Tuning Reactor

The tuning reactor for a filter must be specified to carry the RMS and harmonic currents it will be exposed to. We recommend including a complete spectrum of what the reactor will absorb during its worst case condition of harmonic absorption. With this information, the manufacturer can derate their design for heating according to the harmonics passing through the filter. In addition we would recommend the following items be included with a filter reactor:

- Taps for fine tuning and adjustments.
- High Q, i.e. an X/R of at least 50.

Tuning reactors can also be constructed with either an air core or an iron core. Air core reactors are larger and are excellent for outdoor applications. Iron core reactors on the other hand are much more compact and work well in metal enclosed equipment. Iron core reactors cannot be specified as outdoor equipment. Besides these factors, cost and reliability should be considered before deciding on either one for application.

12.0 Connection Arrangements

The capacitor banks of notch harmonic filters will in almost all cases be connected in an ungrounded wye configuration. This falls in line with plain capacitor bank installation guidelines. There are only a few exceptions to this arrangement, and those are:

- Zero Sequence 3rd Filters - If this type of filter is constructed, it must have a grounded wye connection arrangement for the 3rd harmonic (that is zero sequence in this case) to be trapped.
- Low Voltage Filters - Low voltage delta connected filters that can be designed within capacitor peak voltage stress limits, can be used. The delta arrangement increases voltage across the 600 V standard capacitor units so that more reactive power is supplied. Thus, the $/kVar drops as compared to wye connected units.

13.0 A Few More Suggestions

Here are a few more suggestions to consider. At a later date, more material may be added to cover these in more detail.

1. Make sure that you use the power flow feature in EasyPower to check voltage conditions before and after a filter is connected. Often a large harmonic filter will increase voltage on the bus to the point that a supply transformer tap has to be adjusted to keep voltage near 100% of nominal. To do this you will need to have a properly defined case to run power flow, which includes loading information and proper voltage set points on generators.
2. Make sure to check the “Calculated from Power Flow” option in the Control Tab of the Harmonic Options. This will cause RSS and other quantities that use fundamental to use those determined from the a power flow simulation. Again, to do this you will need to have a properly defined case to run power flow, which includes loading information and proper voltage set points on generators.
3. Remember to keep cable runs to filters very short. This mean that filters must be located near the bus of application. If the cable length is excessive, the reactance in the cable will detune the filter. If the only location for a filter is a long distance from the main bus, you must adjust tuning of the reactor so that the combination of the cable and reactor impedance supply the appropriate tuning at the bus of application.

4. The FilterDesing.xlsx spreadsheet supplied is based upon a wye-ungrounded configuration. Use the spreadsheet at your own risk. You must validate all of the numbers put in and calculated from yourself. If you make improvements, I would love to have them, and I can then circulate them to the other webinar attendees.
5. The filter reactors automatically tame the transient inrush condition when the filter is switched in. Thus a filter is quite a bit safer to close into a system than a bare capacitor bank without surge reactors. A bare capacitor bank will cause a transient voltage condition, ringing between a quarter cycle and a cycle. Ring times are typically longer for medium voltage systems, and shorter for low voltage systems (due to higher resistance and lower X/R ratio of system components).