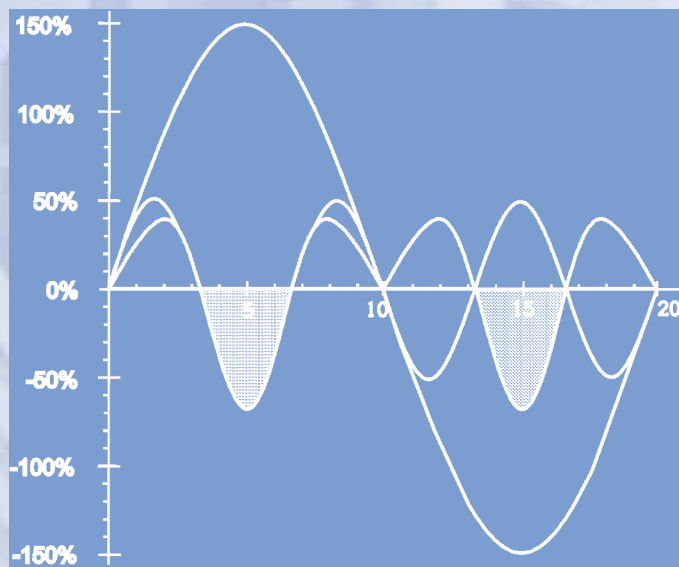


# Power Quality Application Guide



## *Harmonics* *Passive Filters*

3.3.1



# Harmonics

## Passive Filters

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# Harmonics

## Passive Filters

### Basics

In Section 3.1.2 of this Guide it was explained why reactive power should be compensated and how this is best accomplished. Fundamental reactive power is always an onerous oscillation of energy. When considering harmonic currents it is not so clear that they can be addressed as a second type of reactive power. Harmonic currents may originate from systems in which there is no energy and where the sign of the (composite) current matches that of the voltage throughout the cycle (e.g. a phase-angle controller for an incandescent lamp). The term 'wattless current' is sometimes applied to the harmonic current when there are no substantial voltage harmonics of same orders to multiply them with – the product of current and voltage for an individual order being zero. However, harmonic currents have a lot in common with reactive currents:

- ◆ They are both undesirable in that they require part of the capacity of generators, cables, and transformers, while contributing nothing to the generation and transport of electrical energy.
- ◆ They both cause additional losses – because the voltage drop is phase related to the current so the product is real and non-zero.
- ◆ Harmonics originate mostly from the power-consuming load and flow back to the energy source, against the normal energy flow (Figure 1). (An exception is a renewable energy source connected to the grid by a power electronic converter, where the harmonics flow from the source.) Fundamental reactive power does not have a defined direction - intake of inductive reactive power is synonymous with output of capacitive reactive power and vice versa.

It should therefore be possible to combat both reactive power and harmonics by similar means. This is indeed the case and the topic of this application note. The basic facts are restated below in slightly more detail to ensure a thorough understanding of the information presented in Section 3.1.2.

- ◆ Inductances,  $L$ , and capacitances,  $C$ , have less in common with resistive elements than might be assumed. In practically all electrical engineering literature, including this Guide, they are classed as linear devices, i.e. that current is proportional to voltage. In fact, this is valid only for a pure sine wave. When considering the instantaneous values, voltage is proportional to the **change** of current per time in  $L$ , and current is proportional to the **change** of voltage per time in  $C$ . This leads directly to the next point.

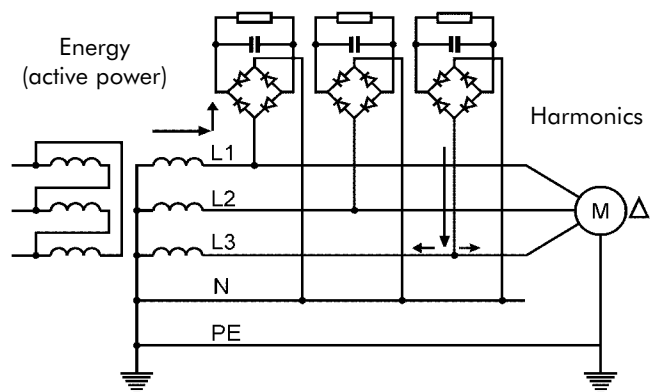


Figure 1 - Harmonics originate from the load and flow 'upstream' towards the supply

- ◆ In a resistive element, a sinusoidal voltage drives a sine current, and a sine current causes a sine voltage drop. Accounting for the proportionality between them this is trivial. In a reactive component, a sine voltage also drives a sine current and sine current causes a sine voltage drop, although this is far less trivial. To be more precise, it is not even true. A sine voltage, if applied to a capacitor, drives a cosine current through it, and if applied to a reactor, drives a **negative** cosine current. This does not really change very much in practice, as sine and cosine have the same waveshape and only a different starting point, i. e., a different phase angle. (In reality, while the phase angle is of interest, the starting point is of no interest and has no influence.)

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These considerations lead to the following points:

- ◆ Voltage waveshapes other than sine, when applied to reactive components, do not result in a current of similar waveshape. Rectangles become triangles, straight lines get bent, and slopes become straight. The reverse is also true because of above-mentioned proportionality.
- ◆ The resistance of an ohmic element, sine or not, AC or DC, is in principle constant if skin effect is ignored. With inductive components, however, reactance rises proportionally with frequency. In capacitive components, reactance drops proportionally with rising frequency. This has consequences for their behaviour under the impact of non-sinusoidal voltage and current waveforms which both, as mentioned above, deviate from each other. These waveforms can be represented as an infinite multitude of different frequencies (so-called Fourier analysis). This behaviour may incur certain risks such as capacitor overload mentioned in Section 3.1.2 but can also be taken advantage of by the use of passive filters.

## Dedicated filtering circuits for individual frequencies

A given  $L$  and a given  $C$  have equal absolute reactances at a well-defined frequency, the so-called resonant frequency:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

Moreover, one of the components has a phase shift of  $90^\circ$  and the other of  $-90^\circ$ , referring to the currents if both components are connected in parallel and to the voltage drops across each of them if they are connected in series. For harmonic filtering, the series  $LC$  connection (acceptor circuit) is normally used, while the parallel (rejection circuit) is applicable in only a few special cases. This Section considers only the series connection. The two voltage drops (i.e. those across the inductance and capacitance) have a mutual phase shift of  $180^\circ$ , i. e., inverse polarity. Even without resorting to complex geometry at this point, it is obvious that the  $L$  and  $C$  reactances in a series  $LC$  filter **subtract** from each other rather than adding up, or in other words they do add up but have opposite signs, which is the same. At resonance frequency, where the magnitudes of their reactances are equal, they subtract to zero. Therefore an acceptor circuit is practically a short circuit at this particular frequency. Only the resistance, mostly of the reactor winding, remains to be considered, but that can be made sufficiently low.

The series tuned circuit behaves as an acceptor (i.e. a low impedance path) for current at the frequency to which it is tuned. It is used to compensate for the harmonic currents produced by an item of equipment or a group of items so that the harmonic currents do not flow back to the supply. The harmonic current originates from the load and flows back towards the supply source and the acceptor filter where it divides according to Kirchhoff's Laws in inverse proportion to the impedances. Since harmonic current is flowing through impedance, harmonic voltages are generated that appear as distortion on the supply voltage. The purpose of the filter is to reduce the magnitude of harmonic current that flows back onto the supply network and, consequently, the harmonic voltage distortion that would otherwise result. Note that, if you want to reduce the potential voltage harmonic of a certain order by more than 50% with an acceptor circuit, it must have lower impedance than the network's short circuit impedance at that specific frequency.

Because there are losses in passive filters and reactive compensators some energy is lost as heat. As usual, keeping losses low requires more material – larger cross-section conductors, with better, and more, magnetic steel – and therefore increases the cost. In extreme cases, using low cost (=high loss) units means that the money saved through compensating reactive power is lost instead as active losses in the compensator. After all, the charge for reactive power is normally not as high as for active power. The magnetizing and eddy current losses in the steel and the dielectric and ohmic losses in the capacitor are normally so low that they do not need to be taken into account as far as the behaviour of the filter is concerned. However, these losses result in the generation of heat and are an important design consideration; they are the reason for overheating and subsequent failure in overload conditions. Losses also influence the filtering quality, that is to say, the sharpness of separating the wanted from the undesired frequency is a lot better when losses are low. In order to assess the quality a quality factor is defined, incurring the quotient of reactance by resistance.

## Reactive compensation

Reactive current compensators are affected by harmonics (as explained in Section 3.1.2 of this Guide) and it is recommended that power factor correction capacitors are de-tuned. In fact, some electricity suppliers require de-tuning.

'De-tuning' means connecting a reactor in series with the PFC capacitor so that the capacitor/inductor combination behaves as a capacitor at the fundamental supply frequency but has a defined behaviour for harmonic frequencies.

A simple (non de-tuned) PFC is actually part of an acceptor circuit formed with inductive components in the network, especially with stray inductance from transformers. Resonance will lead to excessive harmonic currents and to excessive voltage drops in the proximity of transformers affected.

It has been explained that, at the tuned frequency, the magnitude of the voltage drops across the inductive and capacitive elements is the same but with a 180° phase difference, giving a resultant 'zero' voltage drop. However, at or near resonance, the voltage drop across each element is much higher than that would be expected across, for example, the network impedance at the point of common coupling. So, considering the elements individually, each has a high magnitude voltage drop across it even though the resultant voltage drop across the combination is small. This explains why 'accidental' acceptor circuits (e.g a PFC capacitor with stray inductance) are a problem – the installation is across the capacitive element and sees these amplified voltages. When the inductive element is added intentionally, the installation is across the resultant acceptor voltage drop. The excess voltages remain inside the compensator cubicle, say across the capacitors designed for these voltage values, but at its outside terminals no resonance or magnified voltages can appear.

It is worth remembering that, especially where single phase non-linear loads are in use, there are harmonic frequencies at 100 Hz intervals from 50 Hz to well over 1 KHz so there is ample scope for resonances to be excited.

## Combined compensation and filtering

In practice, the functions of reactive power compensation and harmonic current filtering are often combined. It is usual to set the resonant frequency of the  $LC$  circuit at a non-harmonic frequency because compensators may easily be overloaded. The rating of the reactors is normally given as a percentage of the rated reactive power of the capacitors at 50 Hz. For example, a 5% de-tuning rate means that  $1/20$  of the voltage drops across  $L$  and  $21/20$  drop across  $C$ , **subtracting** to 100% overall. At 20 times the frequency, say 1,000 Hz, the ratio would be reversed, so the resonant frequency where  $X_L$  and  $X_C$  are equal lies in the middle between these two frequencies, to be precise at:

$$50 \text{ Hz} * \sqrt{20} = 224 \text{ Hz}$$

Another common value, 7%, yields a resonant frequency of 189 Hz, thus avoiding an approximate short circuit for any harmonic. Because the  $LC$  combination is across the supply network, harmonics from external sources can flow through it just as easily as the internal sources for which it was designed. Therefore, if you operate such a filter but your neighbour does not, you may have to oversize it. In any case, oversizing will not only avoid unforeseen overload but also improve the filter quality, that is, separate the desired from the undesired frequencies more sharply, with reduced energy losses. This effect is reduced if the installation is isolated from others by a distribution transformer with its associated inductance.

Active harmonic conditioners (AHC) are normally also operated mains parallel (as shunts). Yet, the situation is slightly different. These electronic devices analyse the current harmonics in the load side, and generate exactly these harmonics for the next cycle. As a result, harmonic currents are supplied from the conditioner and fundamental current from the supply. If the total harmonic current requirement is higher than the capacity of the conditioner it merely limits, allowing partial correction and leaving some of the harmonic current to be drawn from the supply.

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AHCs act only on the harmonic currents that are present on the load side, i.e. at the current measuring point. Effectively, this means that, as long as the rating of the AHC is sufficient for the load, the load will not impair the power quality of the supply. If that load is inactive, the conditioner will also be inactive. Section 3.3.3 of this Guide gives further information on the deployment of AHCs.

The passive filter, however, is in a way always active in that it is always on the alert, waiting for 'its' harmonic to show up. Passive acceptor circuits tuned to resonance frequencies of, for example 150 Hz (11% of de-tuning reactance) or 250 Hz (4% of de-tuning reactance), accept any amplitude of the third and the fifth current harmonic, as the name suggests, well into the overload range. This depends on the amount of harmonics found in the mains and does not depend on the impact of one specific load. For this reason they should be generously dimensioned. This is not usually a cost issue when compared to active conditioners.

## Wattless current

As has already been mentioned, where reactive power occurs in a distribution system (usually inductive reactive power), part of the energy in the line is in effect not transferred from source to load. Rather it oscillates from a capacitance to a reactance and back again at a frequency of 100 Hz. For certain intervals of time voltage and current have opposite polarities (Figure 2). Looking at harmonics, the picture appears very similar. In Figure 3 the power of the third current harmonic has been plotted in isolation. The power transferred is the product of the third current harmonic times the voltage present in the line, assuming the line voltage is still a pure sine wave. It can be shown that the areas above and below the abscissa cancel, meaning that at average no energy is transmitted. The third harmonic current is therefore absolutely wattless.

But since harmonics do cause additional losses, there must be some active power associated with them. This apparent contradiction originates from the incorrect assumption that the supply voltage was free of any harmonics. This is impossible, since the moment there is any 150 Hz current flowing, it will cause some – active and probably also reactive – 150 Hz voltage drop. This means that as soon as there is any additional frequency contained within the current, there will also be a certain amount of the same frequency in the voltage. Only when both voltage and current of the same frequency are present can active power occur at this frequency. It should be clear by this point that this will always be the case to some extent. The resistance in the installation circuit causes voltage drop that is exactly in phase with the current and therefore results in real power dissipation whether the current is real, reactive or harmonic.

## Sample measurements

Fluorescent lamps are the only common device where putting the most efficient way of compensation, at the point of origin within the luminaire, is common practice. This is most efficient because only real current flows in the installation wiring, the reactive component having been compensated within the fitting.

When centrally installed units are used, combining the reactive current compensator with the harmonic filter solves several problems at the same time with the same device. The advantage of a centrally installed unit, with appropriate control is that, since not all equipment operates simultaneously, it is often possible to install rather less total compensation capacity than would be the case if all equipment were locally compensated. It also reduces the risk of overcompensating motors. Using a combined filter/compensation device removes

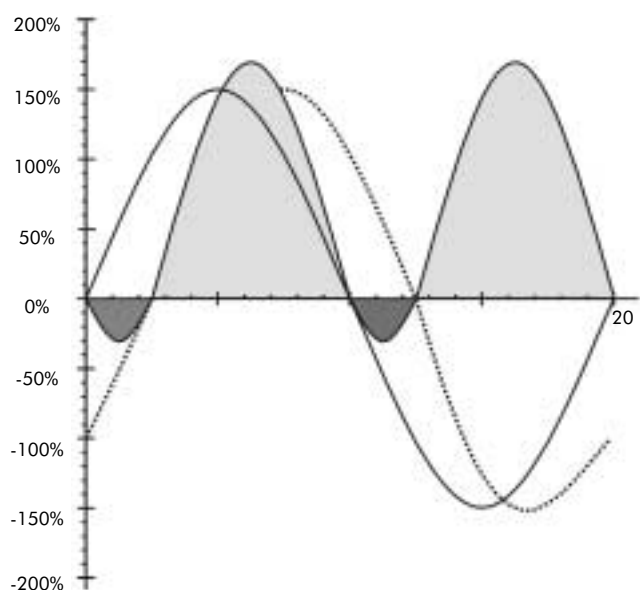


Figure 2 - Fundamental reactive power

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the risk of resonance and ensures that those harmonics within the range of the filter are attenuated.

The risk of attracting pollution from the supply while sweeping one's own is not as high as generally assumed, at least not when the premise is supplied by its own distribution transformer. The voltage drop in a transformer, described in terms of its short circuit voltage, is largely inductive. Therefore, a transformer with a short circuit voltage rating of 4% has a relative reactance of nearly 12% at 150 Hz and close to 20% at 250 Hz. If the neighbouring premises also use their own transformers, the impedance between the two doubles again. However, the impedance of a transformer to harmonics varies a great deal depending upon:

- ◆ The vector group of the transformer, i. e. whether there is any  $\Delta$  winding in there or not.
- ◆ Whether the harmonic in question is triple-n (its order divisible by 3) or other order.

These are topics in Section 3.1 of this Guide and other references [1].

The following series of single-phase measurements will show how acceptor circuits can effectively and cheaply mitigate harmonic problems.

For a single-phase model test, use, for example, two magnetic ballasts for 58 W fluorescent lamps. Their winding resistance is 13.8  $\Omega$ , and inductance 878 mH. Connecting them in series with capacitors, one with a capacitance of 1.3  $\mu\text{F}$  and one with 0.46  $\mu\text{F}$ , provides acceptor circuits with resonance frequencies of 150 Hz and 250 Hz. When connected to the mains in a residential area on a Saturday night during a football match when all the TV sets and a few compact fluorescent lamps are on and the electric stoves are off, the voltage may have a total harmonic distortion (THD) of around 4.7%. This distortion consists mainly of the fifth harmonic contributing around 10 V; the others being insignificant. The third harmonic, though dominating the input currents of TV sets and similar appliances, has little effect upon the voltage as long as the loads are largely balanced (due to the presence of delta windings in transformers). In a single-phase supply, or if only one phase is loaded, this would not be the case. In a usual system, however, with the non-linear loads largely balanced, not very much happens in the 150 Hz filter. But in the 250 Hz filter, one will measure  $\approx 75$  mA of 250 Hz current. This is double the current one finds at 50 Hz, even though a voltage of approximately 230 V is applied to the filter at 50 Hz and only  $\approx 10$  V at 250 Hz. This underlines the basic filtering capability of the method. It has no measurable effect on the supplying voltage, though, because the filter's rating (670 mA, something around 180 VAR) is much too small and its winding resistance much too high to clean up a network loaded with an estimated 400 kVA.

To demonstrate its full capability, the filter model would have to clean up a network of adequate ratings, ideally with a substantial distortion that needs to be mitigated. This can be found if a phase-angle controlled dimmer controlling an adequate load is in the network. An example would be dimming a 200 W incandescent lamp down to 100 W. The dimmer isolates the load from the mains to some extent and thus provides the desired "island" network. Logically, as the controlled load is purely resistive, the voltage across the lamp and the current through the lamp have the same heavy distortions, quantitatively and qualitatively. Can this be mitigated by means of said filters? The answer is yes (Figure 4). Paralleling the affected load with the two acceptor circuits reduces THD of both voltage across and current through the load from  $\approx 61\%$  to  $\approx 37\%$ . In many cases this degree of improvement is just enough to move from a disturbed to a functioning system. Nobody needs an absolutely clean sine wave, except certain measurement labs.

The results also reveal that the 150 Hz acceptor circuit is no longer idling and is in no way superfluous.

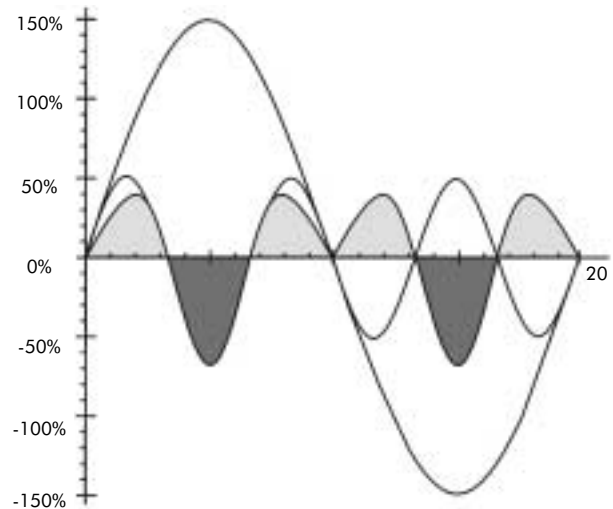


Figure 3 - Wattless power

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Rather, it contributes to the largest part of the improvement. Its current is now 395 mA at 150 Hz (in addition to 22 mA at 250 Hz slightly assisting the other acceptor circuit). The 250 Hz current in the 250 Hz filter is 184 mA, still significant, but less than the 150 Hz current. This is typical for a single-phase load, operated more or less in isolation from the mains.

## How can the performance be improved?

Of course a 350 Hz filter could be added, but that does not address the core of the problem. Despite the presence of third and fifth harmonic filters, the third (34 V) and the fifth (26 V) still each exceed the share of the seventh (Figure 4) even though a 350 Hz filter is missing. The filters under test appear to have a quality problem. Indeed 13.8  $\Omega$  of active resistance is quite high. If the 150 Hz impedance of the third

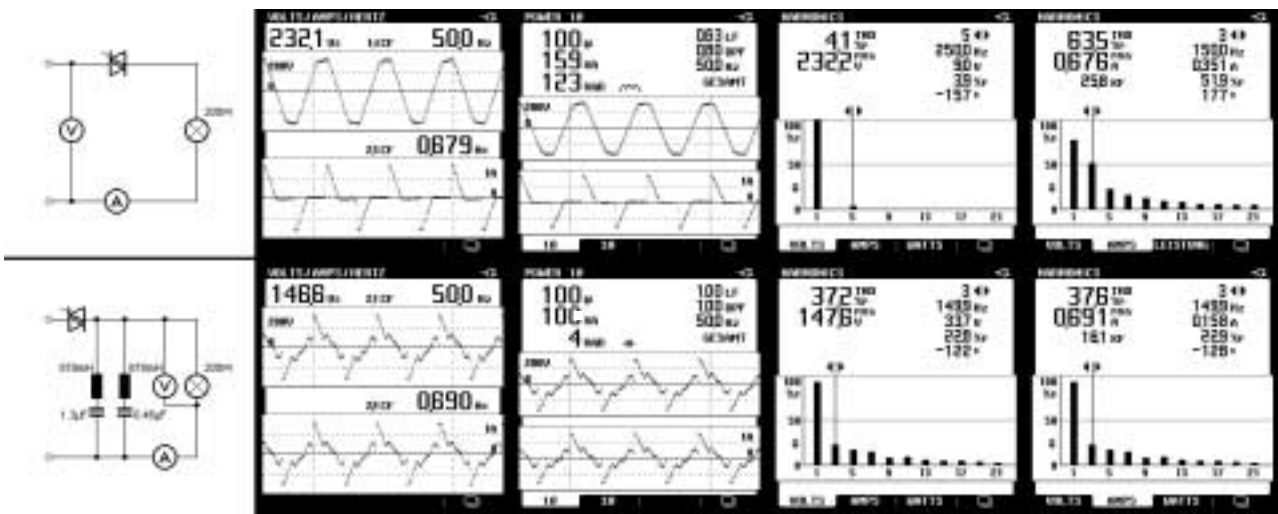


Figure 4 - Voltage and current of a 200 W incandescent lamp dimmed down to 100 W, ordinary and with 3<sup>rd</sup> and 5<sup>th</sup> harmonic acceptor circuits

harmonic acceptor circuit were zero, as it would ideally be, the 150 Hz voltage would also have to be zero. What we find in reality is a voltage of 34 V driving a current of 395 mA in the 150 Hz filter and 26 V driving 184 mA in the 250 Hz filter. Both yield much more than 13.8  $\Omega$ . There must therefore be substantially more losses through eddy currents and hysteresis due to poor steel quality. Inductance vagaries (variation with current, non-constant inductance, etc) hamper a precise tuning to a targeted frequency. This shows how important it is to choose high quality components, especially with respect to the reactor, since it causes most of the losses and inaccuracies. All resistive/eddy current/hysteresis losses end up with inaccurate filter tuning, so it is most important to select dedicated high-quality components instead of using readily available reactors which are cheap but were designed for a different purpose where losses, tolerances and inconsistency of ratings do not matter so much. Passive filtering already is one of the least costly methods of dealing with harmonics. It consists only of a minor modification to the reactive power compensator in operation, so further skimping will turn out quite expensive at the end of the day.

## Central or dispersed?

A further question accompanying the selection of the right model is the star or delta connection. Compensators usually come in delta connection. For a passive filter this arrangement will be only partially effective, since the most prevalent harmonics in office environments (the third) originate from single phase equipment and flow between phase and neutral. There may also be some intermediate solutions with the capacitors connected in delta but designing the de-tuning reactors as three-phase neutral reactors. Your supplier should be able to advise which design is best for your system.

As was stated earlier, acceptors pass harmonic current so that they do not flow back onto the supply. It has

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to be remembered that the harmonic currents still flow around the installation – in fact they provoke an **increase** of TRMS current **between** the source of harmonics and the filter because the loop impedance has decreased. All the measures that should normally be taken within the installation to cope with the effect of harmonic currents are still required. In the presence of a filter, the **sum** of the load and filter currents (i.e. that required to be supplied) is lower than the load current alone without a filter, but the load current alone will be larger than it would have been without any filter in the proximity. From this point of view, highly dispersed filtration is the more efficient solution (since the increased currents flow round smaller loops), although it will be more costly.

Under no circumstances can the presence of any filtering equipment be used as a pretext to return to old TN-C wiring practices formerly used in some countries or to install under-sized neutral conductors (specific guidance on neutral sizing is given in Section 3.5.1 of this Guide). TN-C wiring systems allow neutral currents, including harmonics, to flow in extraneous conductive parts. The disadvantages of the TN-C system, from the EMC point of view, are fully described in Section 6 of this Guide.

De-centralising has to be undertaken with care. Consider two 5<sup>th</sup> harmonic acceptor circuits. They cannot be truly identical, due to component tolerances and differences in operating temperatures. So, for two filters with a rated resonance frequency of 250 Hz, one may in fact resonate at 248 Hz and the other one at 252 Hz. At 250 Hz the former appears capacitive and the latter inductive, and together they form an approximate or even perfect rejection circuit, which has the opposite of the desired effect. Moreover, a 250 Hz current will circulate between the two and may overload both of them as well as the installation wiring (Figure 5). Alternatively, if one of the filters happens to hit the 250 Hz precisely and the other one resonates at, say, 254 Hz, then the larger share of the 250 Hz pollution will use the former and may overload it, while the latter one is idling. Unfortunately this effect will be more extreme the higher the quality factor. After all a higher quality factor of an acceptor/rejection circuit means nothing else but a steeper decline/incline of impedance while approaching the resonant frequency. Therefore, there must be some impedance between each filter so that they are to some extent isolated from each other and do not appear to be directly in parallel. This implies that wide dispersal of a large number of small filters is not a practical proposition and, as always in engineering, a good balance must be sought.



Figure 5 - What uncontrolled resonance may do

## Mind the L/C ratio

For each frequency there is an infinite number of LC pairs with the same resonant frequency. The value of the capacitor determines the reactive compensation available (which cannot, of course, be zero) leaving the inductor to be specified to determine the harmonic behaviour. Once you make your selection it is fixed forever after. This can be a disadvantage of passive filters. For example, the 150 Hz and 250 Hz model filters discussed earlier drew 50 Hz currents of 100 mA and 37 mA. This is quite low compared to the measured harmonic currents, due to the fact that these filters were designed with a high value of L and a small value of C. One solution is to arrange the filters in smaller groups and switch them in individually to match the reactive compensation required as is done with controlled compensators. Obviously, the filter capacity will also increase as the reactive capacity increases, but this may be desirable because the harmonic current will also be reduced at reduced load.

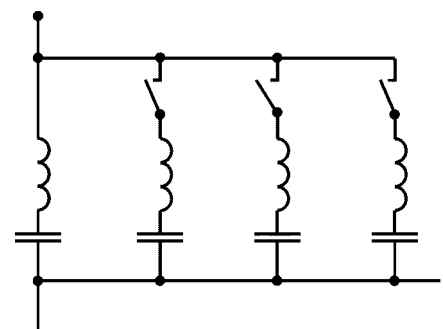


Figure 6 - Combination of acceptor circuit filters

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Consideration should also be given whether to shut off the filters for the higher harmonics when less compensation is needed, as suggested in Figure 6. Though this is not a perfect solution, it is a very cost-effective one. The passive filter we are talking about is nothing more than a modified design or adequate selection of a compensator you need anyway. When applying this method, however, make sure that the cut-out is done top-down (from right to the left in Figure 6) as described in Section 3.1.2 of this Guide. Otherwise one or the other of the higher frequency acceptor circuits may resonate with an inductive network element at one of the lower harmonics.

## Do not filter sound frequency signals away!

Some utilities use sound frequencies to control street lighting, night storage heating, and other systems for demand-side management of the load in their system. Care must be taken not to short out these signals and make them ineffective. The closer the signal frequency is to the resonant frequency of an acceptor circuit, the lower the impedance of that circuit is at that signal frequency. When the installation is fed from a dedicated transformer the associated inductance may well be high enough to ensure that there is no effect on the signalling frequencies. Otherwise it may be necessary to install a parallel LC rejection filter – tuned to the signalling frequencies as shown in Figure 7 (with a utility that uses 183.3 Hz signals, 13/3 of the mains frequency).

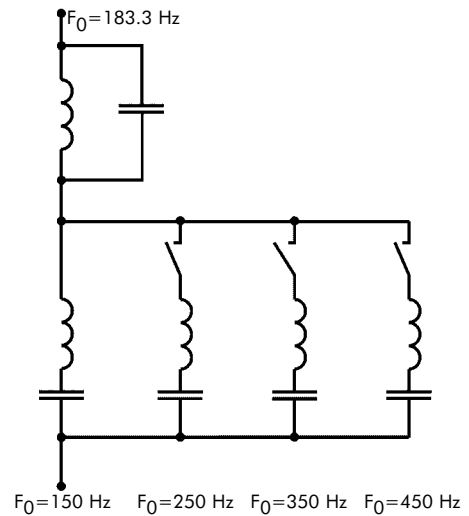


Figure 7 - Combination of acceptor circuit filters with rejection circuit against losing sound frequency signals

## Summary

It incurs very little additional effort and costs to mitigate dominant harmonics together with the compensation of fundamental reactive power, since compensation is done anyway and most compensators today already utilize de-tuning reactors. In most cases, tuning the resonant frequencies of such a system to any possible harmonic frequencies in the power system is deliberately avoided. Greater benefit can be realised by designing for resonance – harmonic currents are more effectively reduced and the risk of overloading the compensator is not as high as generally assumed. A certain degree of reserve, of course, has to be installed. This is not a problem since this brings about a better cleaning effect and better energy efficiency at very little extra cost.

Harmonic currents cause more problems for the supply network than reactive currents so it is foreseeable that utilities will start to charge for harmonics dissipation as well as fundamental reactive power - it makes no sense to charge for fundamental reactive power while not doing so for harmonics.

There is no case where the installation of filtering equipment, except filters installed with or even inside a load, can be used as a convincing argument for failing to up-size neutrals or take account of harmonics in rating cables and other equipment.

Keeping the system's impedance low is of vital importance, even more so with filtering installed than where it is not. Otherwise the filter's effects may be adverse!

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- [1] Fender, Manfred: *Vergleichende Untersuchungen der Netzrückwirkungen von Umrichtern mit Zwischenkreis bei Beachtung realer industrieller Anschluss-Strukturen*, Wiesbaden 1997.

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