Design and application of C-type harmonic filters

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***Abstract*—The connection of large renewable energy generators to relatively weak networks, and associated strict harmonic emission limits for these projects has driven an increasing deployment of harmonic filters, and notably C-type filters in recent years. The article briefly reviews other commonly used configurations and illustrates the key benefits of C-type filters as being reduced losses and excellent mitigation across a wide frequency range. A review of practical requirements of component ratings is presented. Several variants of the filter are presented in order to demonstrate protection requirements and options. Consideration is given to the prospects of standardised filter designs in transmission and renewable applications. Practical aspects of the filter are discussed in terms of switching transients and minimum requirements for reliable commissioning and operation. The article concludes with suggestions as to the origin of the name of the filter and suggestions on terminology.**

I. INTRODUCTION

The field of harmonic filter design can appear to be a combination of art and science. A seminal CIGRÉ document on filter design for HVDC systems [1] aptly describes the challenges as follows:

> …problems in practice arise because of practical limitations — insufficient knowledge of the detail of complex connected power systems, lack of data on the behaviour of components at high frequency, shortage of time and resources in a contractual environment — the usual differences in fact which distinguish real engineering from pure science …

The connection of inverter based energy sources to relatively weak parts of networks combined with strict emission compliance requirements and risk-averse project investors has seen a proliferation of harmonic filters connected at medium and high voltage busbars. A popular choice of harmonic filter topology is the so-called “C-type” filter configuration.

This note briefly reviews some other passive filter configurations, summarises benefits and drawbacks of each, and then provides a broad overview of C-type filter design and provides guidance on the design, ratings, protection and commissioning of these devices.

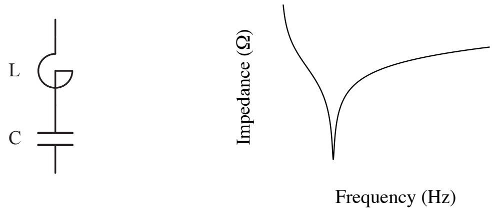
II. PASSIVE TUNED FILTERS

The effect of all passive filters is to modify the equivalent network impedance at one or more frequencies in a manner that presents a lower impedance path for harmonic current emitted by the load to flow into the filter, and for the resulting equivalent impedance to limit amplification of background harmonic distortion. A well designed harmonic filter solution will ensure compliance (i.e., contribution to distortion at a point of connection to within pre-defined emission limits) under all foreseeable operating and network conditions for the expected life of the equipment.

The components or building blocks of passive filters — inductance, capacitance and resistance — can be configured in many ways to achieve this goal. The following are practical implementations in common use:

A. Single tuned filters

The single tuned filter is a series combination of a capacitor (C) and an inductance (L). The inductance consists of several windings of a conductor such as aluminium and copper and therefore has an inherent, internal resistance (R). This common configuration varies significantly in terms of application, determined mainly by the selection of inductance.



A capacitor bank fitted with a relatively small (in terms of fundamental frequency reactance) inductor that serves only to limit current during energisation — especially back-to-back energisation of more than one bank at the same busbar — is not usually intended for filtering applications but rather for voltage support or reactive power compensation only.

When the inductance is chosen to ensure minimum impedance at a frequency where little or no harmonic distortion is expected, the combination is referred to as a detuned capacitor bank. The vast majority of existing industrial, distribution and transmission sector capacitor banks fall into this category. Provided that harmonic conditions in the network are determined largely by so-called characteristic harmonics, originating from controlled or uncontrolled rectifier operations, detuned banks are unlikely to create harmonic resonance problems to the network and their design and ratings are relatively simple and reliable.

A capacitor and inductor tuned to a specific harmonic order can be referred to as a notch filter. The relatively low loss inductor and capacitor result in very low impedance at the tuned frequency and act as an effective drain for harmonic current at that frequency, and that frequency alone. The sharpness of the notch, also referred to as the quality factor of the filter, is determined by the resistance of the inductor [2].

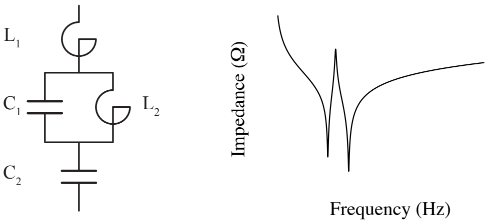
$$Q \quad = \quad \frac{1}{R}\sqrt{\frac{L}{C}} \tag{1}$$

The inductor manufacturer has some control over the internal resistance R. For example it is possible to design an inductor that has very low losses (resulting in a very high Q filter), normally at higher material cost. It is also possible to increase the resistance of the inductor within the bounds of increased losses and winding temperature. It is advisable to consult with manufacturers prior to selecting the Q factor of a single tuned filter to ensure the resulting components are practical.

The single tuned, undamped harmonic filter is good at providing a low impedance path for harmonic current, diverting the current away from the upstream network and hence reducing harmonic distortion at the tuned frequency. It is relatively simple to manufacture, construct and protect, and has a small footprint. It is useful in applications where performance does not rely on accurate knowledge of network impedance variations and when distortion at one, or in the case of a number of parallel connected single tuned filters, a limited number of dominant harmonic orders is to mitigated. On the other hand the single tuned undamped filter is only good at mitigating a single harmonic order, is sensitive to component tolerances and its low impedance at a frequency where there may be significant background harmonic distortion caused by non-linear loads elsewhere in the network can make component ratings difficult to determine accurately, frequently resulting in either over- or under designed outcomes.

B. Double tuned filters

Double tuned filters are combinations of two inductances and two capacitances that present two tuned frequencies. From a network perspective these filters are equivalent to two single tuned filters connected to the same node. These filters have the advantages of a relatively small footprint compared to two separate single tuned filters, the ability to fix a rejection frequency (the parallel resonant frequency between the two low impedance tuned frequencies) that can be useful for applications where audio frequency load control systems are deployed on the same network. The downsides of this configuration are shared with single tuned filter. Additionally, the relatively complex mechanical configuration of the hardware can make access during and after construction difficult. Special care is also required in the consideration of potentially large circulating current in the tank circuit.



An important consideration for all harmonic filter design is illustrated in the above graph of frequency dependent impedance of the double tuned harmonic filter: while the combination of two tuned frequencies result in low impedance at those frequencies, the unavoidable high impedance between the two will result in amplification of harmonic distortion, and poor selection of tuned frequencies, component tolerances and unpredictable network impedance and background harmonic distortion may result in worse performance than expected.

Notch filters, be they single or double tuned, are effective in networks where harmonic sources are known, concentrated at specific, limited harmonic orders, and where the impact of background harmonic distortion is known and not significant.

These conditions are frequently absent, and filters with lower Q values are required in many applications. When the internal resistance of inductors cannot achieve the required damping, additional, external resistors are added to the filter circuit.

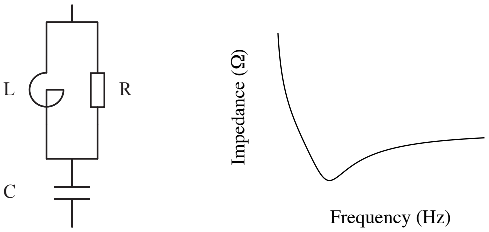
III. DAMPED FILTERS

Damped filters are a broad category of filters that include a discrete damping resistor as an additional component. Any filter configuration where a resistor is specifically included for the purpose of increasing the bandwidth of tuning (i.e., lowering the Q) is referred to as a damped filter.

It is therefore possible to configure damped single tuned or damped double-tuned filters, generally by simply placing a suitably rated resistor in parallel with the inductor. Advantages of such damped filters are lower sensitivity to component variation, and a wider range of frequencies at which a lower impedance is presented to the network. Note that damping resistors are almost never placed in series with the filter circuit due to the high losses at fundamental frequency and basic constructibility of devices that can withstand full rated filter current and short circuit currents.

A. Single tuned damped filters

The single tuned damped filter is similar to the undamped single tuned filter described above with the addition of a discrete damping resistor across the inductor. The impact on frequency dependent impedance is clear — less sharp notch filtering at the tuned frequency and a lower impedance across a wider band of frequencies.



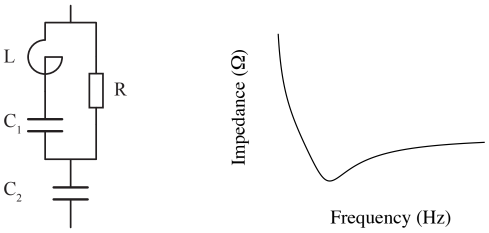
Such a filter arrangement is effective across a wider range of harmonic orders, and the designer has much more control over how wide that range is by selecting an appropriate value for the damping resistance. The damped filter is less susceptible to changes in the network and the performance is not normally critically related to the possible component tolerances of the filter components.

A clear disadvantage of the damped single tuned filter is the relatively high fundamental frequency losses dissipated in the damping resistor — proportional to the square of the fundamental frequency current flowing through the inductor, in other words to the square of the reactive power of the filter bank.

B. C-type filters

The C-type filter configuration is a special implementation of the single tuned damped filter in the sense that in the frequency domain it can be made to exhibit minimum impedance at a single frequency and that the bandwidth around the tuned frequency can be defined by selection of a damping resistor.

These filters are formally part of the class denoted as third order damped harmonic filters based on the three energy-storing elements in the arrangement:

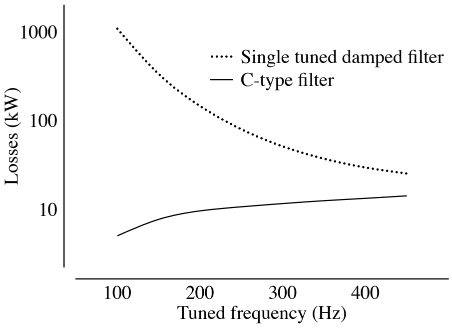


Comparison of the impedance characteristic of the above damped single tuned filter and the C-type filter illustrates the similarity in terms of frequency dependent impedance.

C-type filters add damping to the network by contributing shunt conductance. Most adverse harmonic effects are caused by the interaction of inverter-based generators or loads producing resonances at harmonic frequencies between their low-loss components and the impedance of the supply system. The C-type filter can add a significant shunt conductance over a broad range of frequencies, thereby damping numerous potential resonances and lowering the high harmonic voltages that they can cause.

These filters have an auxiliary capacitor C_1 in series with the tuning inductance L, and a damping resistor R across this combined tuned circuit. Component values for L and C_1 are selected such that series tuning (i.e. minimum impedance) occurs at the network fundamental frequency. The resulting low fundamental frequency current in the damping resistor is a very useful feature, and especially in cases where the application requires a low tuned frequency.

The superior performance of a C-type filter compared to a single-tuned damped filter is clear from the below loss comparison. In this example both filters are damped to the same degree, with the same tuned frequency and fundamental frequency reactive power rating.



This comparison is of course only valid for a specific set of background harmonic distortion, load or generator current emissions, selection of damping resistor, and inductor loss factor. The cost of losses is to be evaluated in each case with consideration of the additional cost of the C-type auxiliary capacitor and possible associated protection equipment, the additional mechanical complexity and hence installation and maintenance costs, the capitalised cost of losses, and the duty cycle of the filter. As a general guideline the application of C-type filters tuned above the fifth harmonic has not been shown to be economically justified.

The advantage of lower fundamental frequency losses is obtained by careful selection and control of the values of C_1 and L in the design and manufacturing process. Designers may be tempted to specify very narrow tolerances on these values to reduce the losses in the damping resistor, but practical realities of component design and manufacture should be taken into account to ensure a reasonable outcome.

IV. DESIGN CHALLENGES

Practical applications of harmonic filters are usually faced with a recurring set of challenges:

- The frequency dependent impedance of the network varies significantly over the short and long term as a result of network operating modes, contingencies, and network loading conditions that may require more or less capacitive or inductive shunt compensation in the wider network.
- The load or generator wishing to be connected to this network may operate under a variety of power levels, each with unique harmonic current emission and each with unique frequency dependent impedance. Inverter emissions and internal impedance can vary significantly depending on load level.
- The load or generator normally consists of a network of cables, transformers, and overhead lines that can be operated in many possible configurations, each with different complex impedance. Complete sections of the load or generator may be disconnected for extended period of time for example for maintenance.
- Network planning or regulatory authorities may allocate relatively small emission limits to the load or generator depending on system strength, pre-existing conditions or perceptions of risk.

To further complicate matters, many of the above parameters are not known with great certainty, meaning that any mitigation design is expected to be effective when all the stated parameters are as presented, and with leeway to ensure compliance to emission limits is still achieved even when key inputs such as network impedance is not as expected.

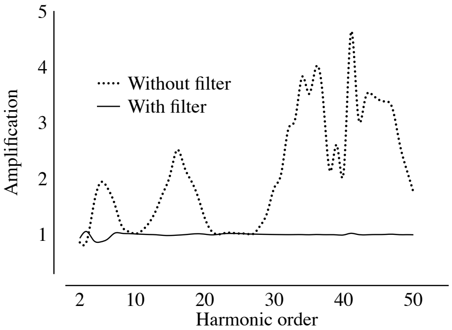
Filter designs should be pragmatic, effective and robust. That means the filter is appropriately designed and rated according to good engineering judgement, that it results in the required mitigation of harmonic distortion under all foreseen present and future operating modes, and that it will remain reliable and effective for the life of the load or generator.

Cooperation and information sharing between stakeholders are essential to achieve this outcome:

- The network operator or owner is responsible for the long term management of the network, to provide reliable information on possible network impedance values and to provide guidance on the worst case background harmonic distortion that can be expected at the point of connection. The network operator should also clarify the expectations in terms of pre-connection assessment studies and how compliance will be verified post-connection.
- The owner of the load or generator is responsible for compliance and can determine the nature of the plant, including harmonic sources, and the possible operating modes of the plant.
- The filter designer applies engineering judgement to define a filter solution that ensures compliance under all possible long term operating modes, network conditions, and with consideration of unknowns, uncertainties and tolerances in input information. This includes the boundary conditions of considering the network background harmonic distortion ranging from zero to the maximum stated by the network operator, and with consideration of the possible impact of amplification of background distortion due to the connection of the load or generator.

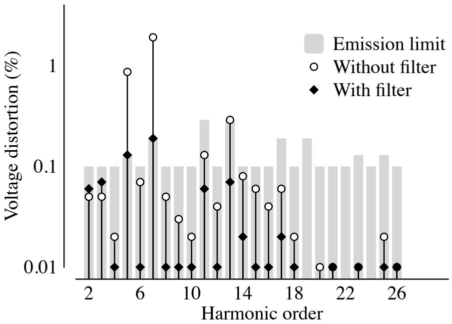
Good filter design comes with experience. There is no single correct filter solution in any application, and selecting a solution resists formal optimisation methods, mainly because of the large number of variables (in terms of network, plant and filter parameters and configurations) and difficulties in obtaining accurate costing and layout details for several considered options in a timely manner.

The following two graphs demonstrate a typical good outcome. The maximum amplification factor under all possible operating modes, under all load or generator operating conditions, and taking into account worst case component tolerances is compared with harmonic filters connected, and not connected. This specific comparison is for a solar farm during night time operation, and demonstrates the need for the harmonic filter to remain connected during night time when the solar farm inverters are disconnected but the collector cable system and transformers remain energised.



The pertinent conclusion from this graph is that under all conditions background harmonic distortion, that is, distortion from other sources in the network, will not be amplified by the presence of the solar plant, an outcome that would clearly be welcomed by the network operator. The same evaluation is also done during day time to ensure good behaviour at all times.

The comparison below demonstrates that the harmonic filter performs the required task very effectively: emissions are maintained to within limits when the filter is connected, whereas significant non-compliances are expected without the filter in service. As before, the worst case outcome under all operating modes, under all network conditions, considering tolerances or uncertainty in plant component values, and tolerance in filter components are included in the results.



The graph compares the expected emissions of the plant as seen at the point of connection when there is no background distortion. It is an important aspect of filter design as it ensures compliance with emission limits only considering the impact of the plant injecting harmonic current (from all sources in the plant, such as inverters and transformer excitation current) into the combined impedance of the network and the plant. A separate and equally important aspect is to also review the contribution of the plant to the distortion at the point of connection when background harmonic distortion is also considered.

V. Equipment design and ratings

Harmonic filters, like all electrical equipment, must be rated to withstand the site and operating conditions and electrical environment in which they are expected to be in service for several decades. Selection of appropriate components and ratings require a comprehensive understanding of these conditions, the standards that guide application and rating of the various components, and the practical consequences of component selection on manufacturing and lifetime cost.

A. Site conditions

Site conditions include all aspects of climate (including minimum and maximum temperatures, wind, solar irradiance, altitude above sea level, precipitation, and humidity), seismic activity and atmospheric conditions, including pollution levels and presence of conductive dust. Possible wildlife such as snakes, possums, birds or insects that may interfere with the equipment is to be considered.

Site constraints need to be taken into consideration too, for example footprint or height limitations, and maximum permissible audible noise generated by the equipment. Site preferences also contribute to the overall design of the equipment, for example in the selection of types of insulating material for bushing material as a standard for a given location, or site specific requirements for safety, construction or maintenance access.

An important but often overlooked aspect of site conditions relates to the potential challenges posed to transporting the equipment from the manufacturing location to the site. Access, road conditions and availability of local storage facilities may have a material impact on the design of the equipment and its preparation for shipping.

B. Operating conditions

Operating conditions relate to how the filter will be used, and importantly, how it will be controlled. The typical daily and long term worst case and average switching operations the equipment will be subjected to can be a significant factor in component material selection and ratings. At the very least it should be known whether the standard capacitor discharge and reconnection times are relevant.

C. Electrical environment

Steady state, short term, and transient events are all important aspects of the electrical environment to which the filter will be exposed.

In the absence of explicit requirements for component ratings, manufacturers may rely only on available information and the application of the relevant standards for each component. This may result in significant over- or under design:

- The reference values for both long-term effects and very-short-term effects to which electrical equipment can be exposed is is presented as compatibility levels [3],[4]. The steady harmonic voltages and the associated short term (< 3 s) effects can be difficult to apply in filter design as the standard does not provide guidance on the harmonic spectrum that should be applied across the filter, and applying the stated compatibility levels at the tuned frequency can result in overly conservative component ratings.
- Ignoring, or not specifying the expected fundamental frequency and harmonic conditions in which equipment must operate may result in design based on overly optimistic assumptions with impacts on reliability, life expectancy and safety.

Foreseeable electrical operating conditions include exposure to all known upstream network configurations, all possible configurations of the connected load or generator, variations in the filter component values due to tolerances, temperature variations or ageing, and fundamental frequency changes.

Background harmonic distortion often plays a pivotal role in the determination of filter component ratings as the harmonic emissions from the load or generator can be small compared to levels that are permitted in the network. All equipment connected to the network should in theory be able to withstand compatibility levels of harmonic distortion. The problem with compatibility levels as listed in Table 1 of the IEC/TR 61000-3-6 [4] standard is that there are no compatibility levels stated for high voltage systems, and applying the listed compatibility levels as background levels in harmonic filter applications can result in unrealistically conservative ratings.

Careful selection of background harmonic distortion levels in conjunction with load or generation contributions is therefore not only critical in the design process but also difficult to formalise and requires knowledge of the network, filter components and the many trade-offs between reliability, constructibility and life time cost.

The continuous voltage ratings of the capacitor units are calculated using equation 2 in accordance with the requirements of IEC 60871-1:2014 “Shunt capacitors for a.c. power systems having a rated voltage above 1 000 V” [5], that requires the voltage rating of the capacitor be suitably rated to withstand the arithmetic sum of all the voltages (fundamental and harmonic) that may continuously be applied to the capacitor.

$$V_{c,\Sigma} = \sum_{n=1}^{50} V_{c,n} \tag{2}$$

In selecting the capacitor bank voltage rating, the maximum and minimum voltages must be considered, as the above mentioned capacitor standard points out, capacitor element failure is most likely to occur when the voltage across the bank is high. As required by the standard relating to internal fuses, IEC 60871-4 [6], internal fuses are designed to operate correctly for voltages that are greater than $0.9 \times U_N$ and up to and including $2.5 \times U_N$, U_N being the capacitor unit voltage rating. Specifying a very conservative U_N may therefore render the sensitive unbalance protection inoperative. The manufacturer should be asked to demonstrate the efficacy of internal fuses at capacitor bank rated voltage, as well as the range from minimum to maximum network voltage.

The current rating of the inductor is calculated using equation 3 and 4 in accordance with the requirements of IEC 60076-6:2007 "Power transformers – Part 6: Reactors" [7], which requires the inductor be suitably rated to withstand the RMS sum of all the currents (fundamental and harmonic) that may continuously flow through it, noting that the manufacturer is required to consider the frequency-dependent resistance of the reactor and therefore requires knowledge of the full worst-case current spectrum.

$$I_{L,\Sigma} = \sqrt{\sum_{n=1}^{50} {I_{L,n}}^2} \tag{3}$$

The current rating of the parallel resistor is determined in a similar manner according to equation 4:

$$I_{R_P,\Sigma} = \sqrt{\sum_{n=1}^{50} {I_{R_P,n}}^2} \tag{4}$$

The resistor power ratings are to be determined from the expected worst case harmonic current spectrum through the resistor.

$$P_{R_P,\Sigma} = R_P \sum_{n=1}^{50} {I_{R_P,n}}^2 \tag{5}$$

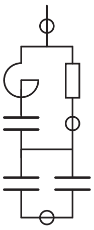
Note that the damping resistor power ratings are based on worst case component shift as well as significant harmonic content at the tuned frequency flowing from the network into the filters. The resistors are therefore designed to withstand worst case network harmonic conditions, while the worst case combination of component tolerances are applied. This is a very important aspect especially for C-type filters: no fundamental frequency losses are expected in the resistor at nominal component values and therefore resistors can be significantly under rated should this fact be neglected.

VI. PROTECTING THE FILTER

The function of a protection system is to remove equipment from service before damage occurs due to internal failures, and to prevent equipment being operated beyond rated capability.

It is possible to protect each discrete component in the harmonic filter by monitoring the current through it, or by detecting differences in current in sections of some components, or by detecting the differences in current between the line side and star point of each phase. Capacitor banks are particularly sensitive to over voltages, including the effect of harmonic voltages across the capacitor banks. Voltage measurement at the junction between main and auxiliary capacitor can provide over voltage protection of both capacitor banks but in most applications the peak voltage across the capacitor banks is derived from the integral of the current through the capacitors.

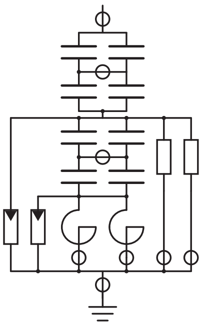
In practise the protection functions below are implemented in protection systems that normally contain specialist protection relays that can measure or calculate capacitor bank over voltage, sensitive unbalance current, and can also monitor and manage the number of energisations/de-energisations of the equipment and the time frame within which such operations take place.



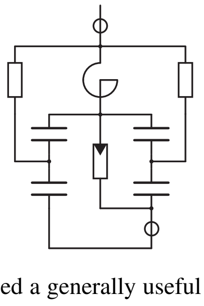
Protection functions:
- Over and under current
- Short circuit
- Earth fault
- Inductor overload
- Resistor overload
- Sensitive unbalance
- Harmonic current
- Peak voltage

The benefits of comprehensive protection of each component in the filter bank must be weighed against the cost of such elaborate protection schemes. The additional cost, for example, of over-current protection of the damping resistor may be mitigated by sufficiently conservative rating of the device so that the additional current sensing in the resistor circuit may not be warranted. Many medium voltage applications of C-type filters do not deploy sensitive unbalance protection of the auxiliary capacitor bank, instead relying on very conservative design (specifically voltage stress levels in the capacitor elements) to minimise the likelihood of an internal failure.

The scheme below is an example of a comprehensive protection scheme typically applied to high or extra high voltage filter banks. In these applications the configuration is commonly referred to as "mechanically switched capacitor with damping network" or MSCDN banks. In these filters the main capacitor bank is generally connected to the line voltage, while the auxiliary capacitor bank, resistor and inductor are connected to the neutral point and the neutral point is usually connected to ground. The scheme illustrates that unbalance protection can be applied to the capacitor banks, resistor and also to the inductor, the latter commonly in practice by means of so-called "split in phase" inductors. The scheme is complemented by surge arresters across the inductor terminals and across the auxiliary capacitor/resistors.



The configuration below is interesting as it combines sensitive unbalance protection of the damping resistor, auxiliary and main capacitor banks and comes at relatively low additional cost (the resistor must have two load side connections and the bank has slightly more complex mechanical arrangement). It should be noted that this layout is only feasible in those cases where internal fuse operation of the auxiliary and main capacitor banks can be detected with sufficient resolution to protect both banks.



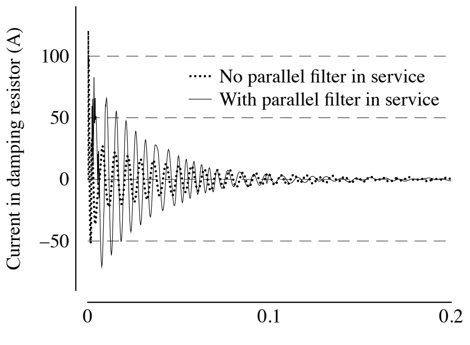
The IEEE has published a generally useful guide for the protection of capacitor banks [8] though some of the protection schemes are impractical for most medium and high voltage applications (such as neutral point voltage transformers requiring compensation against network unbalance.)

VII. SWITCHING

The surge arresters across the capacitors (line-neutral in ungrounded filter banks) in the various configurations above are intended to mitigate the destructive consequences of circuit breaker restrike. Circuit breakers can only be type tested at best to have very low probability of restrike (class C2) [9] and even though the manufacturer can and should be required to provide a statement regarding the suitability of the circuit breaker in each specific application with full knowledge of the application, such an event cannot be ruled out. The consequences of restrike in circuit breakers are expected to be catastrophic failure of capacitor units (case rupture with subsequent ignition of impregnation liquid and fire in the capacitor bank) and possible damage to the circuit breaker itself. The surge arrester across the capacitor bank limits the voltage across the capacitors to a safe value and also reduces the TRV at the circuit breaker. This is a prudent precaution at relatively little additional cost.

Transients arising from filter bank energisation are generally not a concern in terms of circuit breaker capability (the current transient has much lower current amplitude and frequency than the limits in the circuit breaker standard [9] and the filter equipment is designed to withstand such transients. Such transients can be mitigated by means of pre-insertion resistors or controlled switching. [10]. Controlled opening can reduce the risk of re-ignition and restrike by avoiding short arcing times. This is done by allowing a pre-set delay between contact separation and current zero [11]. These active measures may require complex commissioning and ongoing maintenances and cannot be the only mitigation measure or safeguard against restrike as post-commissioning changes to the circuit breaker characteristics may not be detected by the control system causing the breaker to open at sub-optimal points on the voltage waveform.

Filter design should also consider other impacts transient events may have on the filter and its close neighbours. The concerns regarding inrush and outrush due to switching of capacitor banks are largely mitigated due to the considerable series inductance of the filters, transient actions inside filters and adjacent equipment should be considered as well, noting for example the difference below between current in the damping resistor during filter energisation depending on whether an adjacent filter is energised or not.



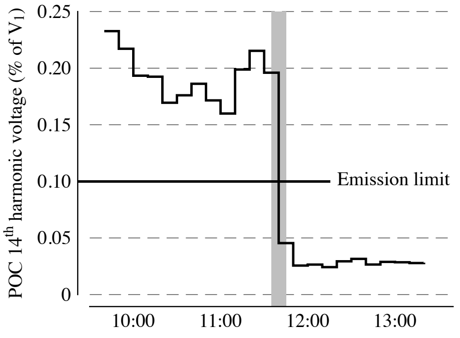
Harmonic filters are intended to establish parallel and series resonant circuits and the behaviour of these circuits, including internally to the filters should not be taken for granted. Most of the work on harmonic assessment and filter design is done in the frequency domain. It is strongly recommended in all cases where reactive power is switched on or off, during normal operation and as a result of an internal or external event such as a fault or voltage instability, that a comprehensive time domain (EMT) switching study be carried out (in addition to the voltage coordination study for the complete installation) that will determine transient voltage stress levels on filter components and switchgear, and provide a basis for surge arrester selection and rating.

VIII. COMMISSIONING AND OPERATION

As part of commissioning of any harmonic filter should be verification of specified and nameplate values, visual confirmation that each component is in good condition, in the correct location and connected correctly. Commissioning tests therefore includes the normal range of visual, electrical and mechanical tests.

A very useful test to conduct is a per-phase frequency dependent impedance test, and comparison to the result expected from routine tested component values. Any deviation can indicate poor or incorrect connections or component placement and the test also confirms the tuned frequency and bandwidth is as expected. A sweep frequency response test device or any signal generator that can deliver sufficient current into the filter bank at a wide range of frequencies can be used for such a test.

It is highly recommended to record the voltage and current conditions (fundamental and harmonic frequencies) at the point of connection of the load or generator to the network and at the busbar where the filter equipment is connected, and the switching transients when the filter is first energised. The short time recording below illustrates the gratifying and immediate impact on a particular harmonic order once a filter solution is connected.



Electrical connections should be verified after a number of load cycles to ensure integrity of connection - either by means of thermal imaging or torque testing.

Ongoing operation of equipment is to be monitored to ensure the equipment remains within intended design parameters. For example, unless specified and rated differently, high voltage capacitor units are not intended to be switched more than a thousand times per year, to avoid excessive stress on internal elements and fuses.

IX. STANDARD FILTERS

C-type harmonic filters can be found in applications from low voltage industrial installations to high voltage transmission systems. Several end users, designers and suppliers have considered defining a standard solution to reduce the amount of detail design, gain from scale in manufacturing, and provide predictable outcomes both in terms of performance and physical dimensions in the substation.

Such solutions could be workable depending on the application. For example, transmission or distribution design may benefit from combining knowledge of long term trends in the wider network with the harmonic performance of the filters and a requirement to install passive reactive compensation for load flow and voltage support in the electrical network.

At individual load level it is more complicated as each point of connection is faced with potentially wide ranging frequency dependent network impedance, generator harmonic performance, reactive power capability and power quality compliance limits. Furthermore, each site may have different pre-existing conditions (electrical or environmental) and plant that require careful integration and analysis, and a custom solution.

X. NOTES ON NAMES AND TERMINOLOGY

The origin of the term “C-type” filter is somewhat of a mystery. The earliest usage in searchable literature is in an article in the proceedings of the IEE [12], where comparisons were drawn between various damped filter configurations. The third filter configuration in an alphabetical list was the C-type and this ordering may have been the prosaic origin of the term. (For the record, the article listed as A-type a second order high pass filter and as B-type a third order high pass filter).

C-type filters have been in ubiquitous use with high power cycloconverters in mining, mineral processing and industrial speed control installations since the early 1970’s [13]. These applications require wide band harmonic mitigation with a filter tuned near the fundamental frequency. The name may therefore also derive from this most common early application.

Inconsistent, overlapping and generally non-descriptive terminology abound in the field of harmonic filters and passive reactive power compensation. The following is offered as demonstration.

Using “Q” to characterise filters can result in confusion. The Q-factor of a passive filter is defined in terms of bandwidth, with more damping resulting in a increased bandwidth and lower Q. Tuning inductors can also be characterised by a “Q-factor” which is defined as the ratio of reactance to resistance at a specific frequency (typically at either the fundamental frequency or nominal tuned frequency). Hence a low Q filter may have a high Q inductor or any other combination of these two identical and related terms. For the avoidance of confusion, it is either necessary to be completely explicit when referring to the “Q factor” of a filter, or to avoid the use of Q altogether and rather specify the amount of damping brought about by specified parallel resistance and the inherent or specified resistance of inductors when exposed to expected current spectra.

Passive harmonic filters are variously described as single- or second-order filters, or single- or double tuned, or damped or detuned, or as low-pass, band-pass or high-pass, not considering the more esoteric configurations such as triple tuned or higher order filters. Capacitor banks that are part of passive harmonic filters can be configured as a single star or double star, sometimes referred to as star, double star, or “wye” connected, or “H” connected. A C-type filter may have a main capacitor bank connected in ungrounded double star and an auxiliary bank connected in H configuration. The main and auxiliary banks can interchangeably be referred to as C_1 or C_2 depending on design software and supplier habits. Some terms can be traced to the basic physical arrangement of the filters, or from roots in signal processing or control theory. Preferences for naming conventions differ from one individual, organisation, standards authority, or country to the next and there does not appear to be a standard naming convention nor firm guideline.

Finally, the inductors used in harmonic filters are commonly referred to as reactors by power system engineers and as coils by manufacturers. There is near, but not complete overlap between these terms.

When discussing or specifying harmonic filters, the author recommends that rather than relying on assuming a common interpretation of terminology, a schematic such as those used in this note, including component values that include references to internal characteristics such as coil resistance, be provided to avoid confusion.

XI. CONCLUSION

The above touched on some important aspects of the design and application of C-type filters, a versatile, effective and relatively simple filter configuration now commonly used at all voltage levels in the network.

It should be appreciated that passive harmonic filters are connected to electricity networks with the specific purpose of changing the resulting frequency dependent impedance in a manner that is mutually beneficial to the network and filter owners (normally the plant or generator owners). Close technical cooperation and information sharing between parties is therefore a basic requirement for successful design and implementation of harmonic filters. This basic requirement will assist in removing much of the uncertainty associated with the wider network that faces the filter designer.

Furthermore, the filter designer should understand that the simple configurations available from power system analysis tools are to be converted into reliable, well engineered and cost optimised solutions by manufacturers, and knowledge of the application environment as well as manufacturing capabilities and limitations, and the expectations of adequately rating and protecting the equipment are essential skills required of designers.

This note was contributed to advance the general understanding and industry knowledge on this topic.

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