

# Harmonic filter design for IEC 61000 compliance

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## Abstract

The paper<sup>1</sup> provides a guideline for the selection of harmonic filters to ensure that compliance to harmonic emission limits is achieved. Three aspects of the process are highlighted:

1. Gathering harmonic information from existing networks and applying the information in the model,
2. Selecting a harmonic filter structure to ensure that compliance is ensured under a variety of situations, and
3. Designing the various filter components to ensure safe and reliable operation under all foreseeable network conditions.

## 1 Introduction

The need for harmonic filter design in power systems is clear: changing loads, capital expenditure-optimised networks and the trend towards distributed generation requires that reactive power compensation devices often have to double up as harmonic mitigation solutions. While power quality standards are now widely known and applied — with the associated proliferation of power quality solutions — the application of these solutions is not always well understood. Good harmonic filter design can appear to be a black art practised by a select few engineers.

A substantial body of knowledge has in fact been accrued over the years: for example a very good

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<sup>1</sup>Presented at the DIgSILENT User Conference, February 2011, Melbourne, Australia

guide can be found in a CIGRÉ publication relating to harmonic filter design in HVDC applications [1]. Careful reading of this and other publications indicate that in most cases experience, detailed knowledge of networks, filters and loads, and realism in the selection of components are the guiding principles in harmonic filter design, and in recent years the process has been enhanced by extremely powerful network analysis tools. The article combines a description of the compliance process with the capabilities of the most powerful network analysis tools to describe a structured approach to harmonic filter design.

The article is presented from the perspective of a medium or high voltage network however the principles are valid for all voltage levels.

## 2 Analysis for compliance

The standard for harmonic distortion emission limits most commonly referred to in grid connection agreements is IEC 61000-3-6 (of which AS/NZS 61000-3-6 is a very close if not verbatim copy) [2].

Jurisdiction will normally determine which standard applies (The equivalent North American guide is IEEE 519 [3]) but all standards essentially operate under the principle that the amount of harmonic emission tolerated from each load in the network is determined by the nature of the network, the nature of the load, and the vulnerability of the network to harmonic distortion.

The emphasis is on permissible voltage distortion in the IEC 61000 standard, the principle being that voltage distortion is seen by all loads connected to a node and therefore compliance results

in safe operation of all connected equipment.

Odd harmonics non multiple of 3			Odd harmonics multiple of 3			Even harmonics		
Order h	Harmonic voltage %		Order h	Harmonic voltage %		Order h	Harmonic voltage %	
	MV	HV-EHV		MV	HV-EHV		MV	HV-EHV
5	5	2	3	4	2	2	1.6	1.5
7	4	2	9	1.2	1	4	1	1
11	3	1.5	15	0.3	0.3	6	0.5	0.5
13	2.5	1.5	21	0.2	0.2	8	0.4	0.4
17	1.6	1	>21	0.2	0.2	10	0.4	0.4
19	1.2	1				12	0.2	0.2
23	1.2	0.7				>12	0.2	0.2
25	1.2	0.7						
>25	0.2 +	0.2 +						
	$\frac{25}{0.5h}$	$\frac{25}{0.5h}$						

NOTE – Total harmonic distortion (THD): 6.5% in MV networks; 3% in HV networks.

Figure 1: Indicative planning levels (extract from [2], Table 2)

One of the most commonly quoted tables from IEC 61000-3-6 is reproduced in figure 1. It presents indicative values of planning levels for harmonic voltage (in percent of the nominal voltage) in MV, HV and EHV power systems. Unfortunately the table is sometimes incorrectly interpreted as being the final word on what power systems can tolerate. Rather, network operators are responsible for setting planning limits for their own networks given immunity levels of the equipment in their network, and must then calculate emission limits according to the procedures in the standard for every new load to ensure their own planning levels are not exceeded. The table is only a guideline, and the standard deals in detail with the process towards setting these emission limits.

The derived emission limits are the compliance limits. They are always lower than the planning limits. Emission limits are generally stated as voltage distortion at a busbar in the absence of other loads or background distortion.

The process of determining emission limits is now implemented at most transmission utilities in Australia, with gradual penetration in distribution and occasionally in large industrial applications.

## 2.1 Compliance process

The purpose of filter design is to provide a design that ensures reliable and safe operation with quan-

tified sensitivity to component parameter changes, frequency variations and network changes. A conceptual process flow is shown in figure 2.

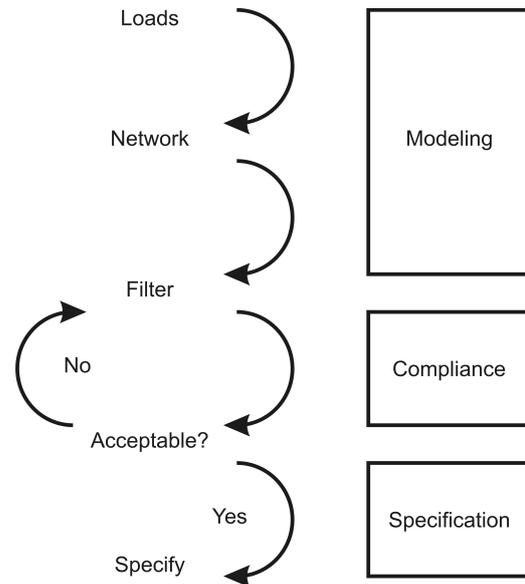


Figure 2: Compliance process

In the first stages of analysis, the focus is on the model that is being constructed — information about the loads that are causing problems, the details of the network and the possible filters that may be implemented. Once a network model is constructed with confidence, filter solutions can be postulated and the resulting network tested for compliance.

During compliance testing, the focus is on ensuring that the solution will meet requirements under all possible operating conditions. Operating conditions can vary as a result of network changes such a substation augmentation, switching or changed generation conditions, and are generally presented by the network planning authority as a set of impedance curves at one or more busbars in the network. New loads may be added, or existing loads removed or changed.

The proposed solution is also subject to variation — changes in temperature or component drift or tolerance can change the behaviour of the filter in a material way.

Whatever the number or type of these possible operating conditions, it is important that they are

quantified and described so that it is clear what the scope of any compliance statement is, and so that any possible non-compliance in future can be referenced to the scope of the study.

Once compliance has been verified, the emphasis moves to design, where reliability and costs become important. A similar approach is used for the analysis for compliance and reliability in the sense that all possible operating conditions need to be considered:

1. Compliance looks at the performance of the network, whereas reliability looks at the filter components. Under compliance testing, all operating conditions are considered and the proposed solution must limit emissions under all of these.
2. For reliability, the worst operating condition is found and the design ensures that equipment is rated appropriately.

### 2.1.1 Loads

Modern network analysis tools make modeling of networks a relatively simple task. Detailed, complex models of networks and loads can be constructed from scratch, or shared across hardware platforms and translated between software packages with relative ease. It can therefore be a trap to assume that the software will do the critically important tasks for you as well, such as ensuring that the loads that contribute to the problem are modeled accurately.

It is highly recommended if at all possible that measurements of existing loads and voltage distortion are recorded, at least at the point of connection of the filter. This has two real benefits: the measured values can be used to calibrate the model (where the model is used to predict for example the harmonic voltage spectrum at a certain bus, which is then compared to the measured values) and it will allow the designer to become familiar with the site conditions such as space, environmental conditions, access, and preferences of operating personnel. Load measurements can of course be scaled for load growth or changes, and should be done with consideration the relevant standard [4]

for such work, so that future measurements can be repeated on the same basis.

It is important to take into account the nature of the load and the type of work that is going to arise from the measurement. For static loads, the situation is quite simple, but presentation of results and further modeling of stochastic loads, where harmonic compliance is closely related to probability distributions needs special consideration.

Care should be taken when using current and/or voltage transformers to measure in medium and high voltage networks. It is accepted that lightly burdened current transformers are quite linear to fairly high frequencies [5], but when the CT burden is high the ratio error becomes large, and in any case the phase error at high harmonics make phase measurement unreliable.

Measuring harmonics in high voltage power systems with inductive and in particular capacitive voltage transformers may cause large errors. For example, tests carried in Norway [6] revealed errors from 80% to +1200% (0.2-12 pu) of correct values.

Inductive voltage transformers can have a relatively small error up to 29<sup>th</sup> harmonic (1450 Hz) while capacitive voltage transformers had large errors at a few hundred Hertz. It is theoretically possible, but practically very difficult to calibrate high voltage instrument transformers, even if such calibration may correct the device phase and ratio error across the measurement frequency range.

Inductive voltage transformers are preferred for harmonic measurements wherever possible, and measurements that purport to indicate direction of harmonic power flow should be treated with great care specifically due to the large phase errors.

### 2.1.2 Network

The process of creating a network is mostly mechanical. Re-using existing models can save time and provide additional confidence in the validity of the model. It is important that all the topology and network variations are built into the model from the outset. Topology variations can relate to changes in fault level, loading, generation, connected lines and planned outages, while network variations include factors such as voltage deviations, unbalance, and

frequency deviations.

Once these variations are documented and agreed, the ability of the model to produce the necessary data for each scenario needs to be tested. It is a good idea for quality management purposes that a record is kept of the output data validity check.

The harmonic analysis tool will in most cases need to be able to

1. perform unbalanced harmonic load flow,
2. analyze inter- and subharmonics, and
3. modeling the frequency dependent characteristics of all network elements.

It is important to calibrate the model — against measurements if at all possible, or against existing studies or known information such as fault level or normal load flow operations — before the real analysis begins.

### 2.1.3 Filters

It is useful to define some general guidelines that must be kept in mind in the selection and application of harmonic filters:

1. Select a filter configuration that is feasible in terms of design and impact on the network,
2. Obtain as realistic as possible model for components: resistance of reactors, manufacturing tolerances of components, sensitivity to aging, temperature,
3. Document the range of variations in inductance, capacitance and resistance, and
4. Keep it as simple as possible: minimum steps, minimum components.

A harmonic filter can be simply defined as a device or combination of devices that is intended to reduce the potentially damaging effects of harmonic voltage distortion (such as increased cost, network losses or damage to equipment) caused by non-linear loads in the network.

A harmonic filter can contain a single branch or a combination of several, it can be located at a single

node or be distributed across several nodes, and it can be active or passive. It is also possible that a harmonic mitigation solution is achieved as part of equipment selection, for example in transformer impedance or vector arrangement.

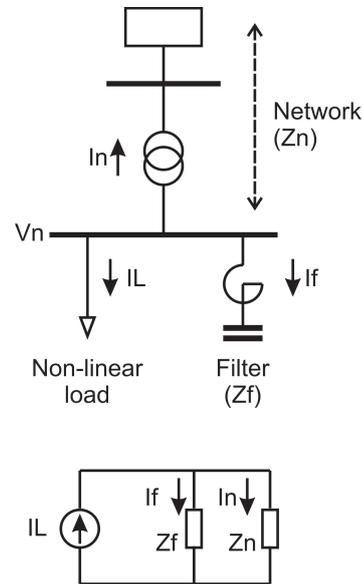


Figure 3: Principle of current divider

A passive filter works as a harmonic filter because it presents a lower impedance path for harmonic current at a particular frequency than the rest of the system, as shown in figure 3. The current  $I_L$  is distorted by the non-linear load. As a result of the current divider consisting of the network and the harmonic filter, with impedance  $Z_n$  and  $Z_f$  respectively, some network current is diverted into the filter according to  $I_n = Z_f / (Z_n + Z_f) \times I_L$ , and the resulting current  $I_n$  flowing into the network results in harmonic voltage distortion of  $V_n = I_n \times Z_n$ .

The filter impedance can therefore be designed to reduce network voltage distortion. The amount of harmonic absorption is a function only of the filter configuration and the network impedance.

The complexity of the task becomes apparent when reviewed against a typical frequency-dependent impedance of a transmission system, such as shown in figure 4. A specific function of harmonic filter impedance must be designed in order to present a relatively low impedance path for

harmonic current at frequencies where harmonic absorption is desired, under all known and possible network conditions.

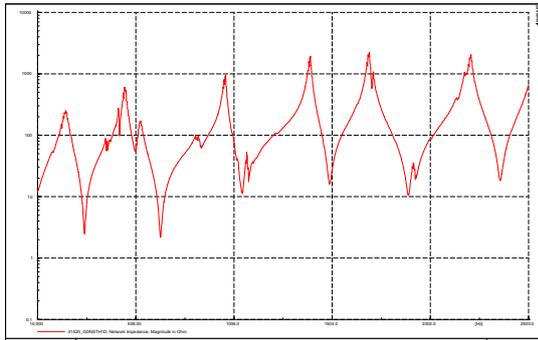


Figure 4: Typical transmission system impedance

The selection of harmonic filter type is determined by many factors such as the allowable reactive power rating (which is determined by acceptable voltage variations when the bank is switched in and limitations on power factor at the point of connection), loss evaluation criteria, available space on site, budget and availability and reliability requirements.

For passive harmonic filters there are a limited number of building blocks – filters are constructed out of combinations of capacitance, inductance and sometimes resistance. The performance of the filter is determined by the rating and topology of these simple building blocks. The topologies for some of the more common filter types are shown in figure 5. The main categories used to describe types (tuned, damping and order) are illustrated in the following description.

**Single tuned** This is the simplest filter topology, consisting of a reactor connected in series with the capacitor bank. By choosing the capacitance and inductance to achieve a series resonance at one specific harmonic order, a very low impedance path, limited only by the resistance in the reactor, is created for one harmonic current. The advantages of this configuration are simplicity, cost, low losses, and unless extremely sensitive tuning is required, stable operation that is not significantly influ-

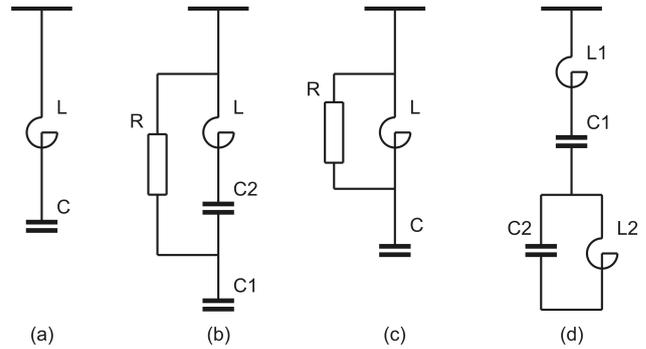


Figure 5: Filter topologies: (a) Single tuned (b) C type (c) Damped single tuned (d) Double tuned

enced by component variations or temperature.

**C type** In this topology an auxiliary capacitor is connected in series with the reactor and is tuned to form a fundamental frequency bypass of the resistor. By creating a tuned filter section C2-L within a 2<sup>nd</sup> order filter, virtually all fundamental current is excluded from the resistor. At frequencies above fundamental, harmonic current flows through R achieving the desired damping.

**Damped single tuned** In this filter topology a damping resistor is connected in parallel with the series reactor. The presence of the resistor broadens out the frequency response of the filter which introduces two beneficial effects: The filter is now less sensitive to the de-tuning effects of frequency drift, ambient temperature variation and component tolerance effects, and the filter response can cover a number of harmonics, therefore it may be possible for example that two harmonic orders can be addressed with a damped single tuned filter. By adding the resistor, filter losses have been increased both at harmonic frequencies where it is needed and at fundamental frequency where it is not. These higher losses can be prohibitive.

**Double (and more) tuned** This type of filter is substantially equivalent to two (or more) parallel connected tuned filters but is imple-

mented as a single combined filter. The reactive power rating of the combined double tuned filter would be the sum of the ratings of the two tuned filters. By combining two tuned filters virtually any Mvar split can be accommodated between the lower and upper frequency components.

This allows the possibility of incorporating a small Mvar rated filter, which on its own would be an uneconomic design, into a larger filter to form a double tuned filter. If two single-tuned branches were used instead, there could be a minimum filter size problem due to connecting a possibly very low Mvar rated filter (as required for one of the two frequencies) on to an HV busbar. This problem can be overcome in most cases by the use of double-tuning. Another advantage is that the double tuned filter has high impedance at a frequency between the two (low impedance) single tuned frequencies, and this frequency can be selected by changing the filter component values. It is therefore possible to create a blocking filter, for example for audio frequency load control systems, by using such a filter combination.

## 2.2 Compliance test

The compliance test compares the stated emission limits of a load or installation as mitigated by a specific harmonic filter solution, with all the possible variations that have been identified as possible and realistic for the network and the harmonic filter. With  $N$  possible topologies,  $K$  network parameters and  $M$  filter parameters that can change,  $N \times K \times M$  can easily result in thousands of discrete scenarios that require evaluation. Common sense can reduce the number of scenarios by eliminating impossible combinations, but the result set will still be very substantial.

This is a task that requires detailed planning before any analysis is done. Analysis software like DIgSILENT PowerFactory can be automated to read in complete sets of parameters of networks, variations in network parameters, and different filter parameters, and can produce the required tests extremely efficiently. In fact, such an automated

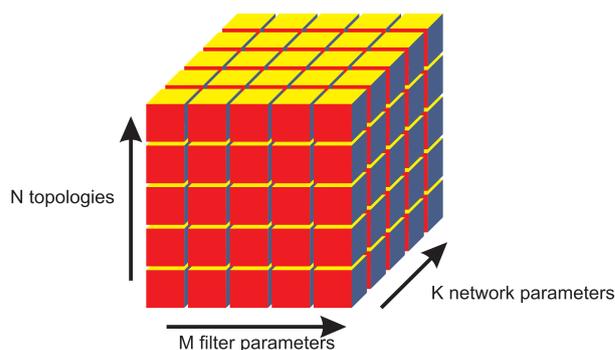


Figure 6: Proliferation of scenarios

process is essential if an exhaustive analysis of anything more than the most elementary networks.

The analysis process typically produces tagged (each result is tagged with the parameters of the scenario that it relates to) sets of harmonic spectra at multiple busbars depending on the scope of the study.

The analysis software can perform all the necessary tests and simply produce a Pass/Fail result but for reporting purposes a clear and compact presentation format is required. This format must not be a subset of the results showing some selected typical outcomes as the selection process can be biased, and it must also not be a comprehensive replica of the results at all the busbars, for all scenarios under review, as this will result in information overload.

A simple tool used in statistical analysis for summarizing data is proposed as a solution. A sensible, compact approach to data representation is the box and whisker plot.

In figure 7 the compliance level is presented as a solid background bar of blue. For each harmonic order, the results from all the simulated scenarios are presented in summary form as a red line spanning from the maximum distortion level to the minimum distortion level. A rectangle shows the spread of values between the 10<sup>th</sup> and 90<sup>th</sup> percentile. This type of graph summarizes information about compliance to emission limits and sensitivity of the solution to network changes that normally occupy large swathes of pages in harmonic compliance reports.

As an example from this graph, it is clear that emission limits for all but the second harmonic

are achieved, and that the solution being evaluated does not achieve compliance at the second harmonic under any circumstances. The large variation in 13<sup>th</sup> harmonic distortion indicates that the solution is sensitive to network changes, and may also require further review.

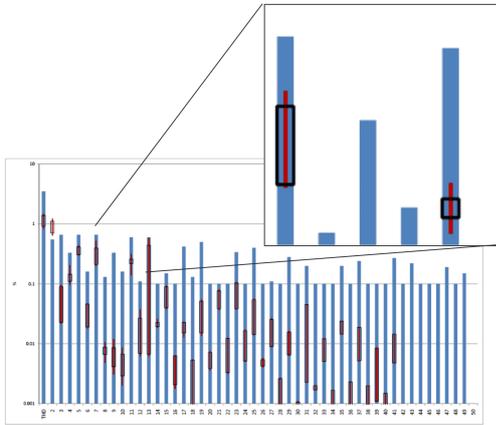


Figure 7: Optimized data representation

With this data representation, the necessary adjustments can be made to filter parameters based on performance in specific scenarios, and the compliance test repeated. Compliance can therefore be reached with an optimal cost solution in terms of capital and lifetime costs.

### 3 Design for reliability

A very similar approach is followed to determine the required component rating. By identifying the worst case voltage stress, fundamental or harmonic current levels in each of the components in the network, the exact safe minimum ratings can be determined with ease.

The various components are rated and specified according to the applicable standards, such as IEC 60871 for capacitor units and AS/NZS 1028 (or IEC 60076-6) for reactors.

Care should be taken in applying the standards, for example the capacitor standard requires that the voltage rating of capacitor units should be equal to the arithmetic sum of all the voltages (fundamental and harmonic) that may continuously be applied to

the capacitor. If a load is known to be erratic or does not operate for long periods, a lower continuous voltage rating may be required than if the load was constant.

Note also a discrepancy that has recently arisen between AS 1028 and IEC 60076-6. For harmonic filter reactors, AS 1028 states that the required current rating must be equal to the RMS current actually expected to flow in the reactor. In IEC 60076, harmonic filter reactors are required to have a current rating of  $1.43 \times I_N$ , the nominal current of the bank, frequently resulting in a much higher current rating (and cost) than if AS 1028 was applied.

Other issues relating to design but not explored further here are those of acceptable sound emissions, seismic and wind loading, and the importance of standardisation.

A description of the various additional aspects of filter design and specification can be found in section 11–15 of the CIGRÉ guide [1]. The most important considerations are described below.

#### 3.1 Transient behaviour

It is of specific importance to review the transient behaviour of the installation — the stresses on individual components during energisation of the installation or nearby equipment may have an important bearing on the short time and impulse withstand ratings of the installation and all the components. Energisation (including de-energization) studies must be carried out, taking into account the nature of point on wave switchgear that may be used. Here the challenge will be similar to that described above for steady state harmonic filter design - to determine with certainty that the worst case condition has been found and quantified. Note that these may arise due to events outside the filter, such as reclose operations of nearby circuit breakers, or transformer energization. The outcome of this analysis will enable the designer to recommend and rate any required impulse withstand and/or surge arresters.

#### 3.2 Protection

Protection of harmonic filters take into account all the normal functions of power system protec-

tion. For the bank, and each branch, consideration should be given to short circuit protection, over-current and earth fault protection, thermal overload protection, over/under voltage protection, and busbar- and breaker failure protection.

Components inside the bank can be protected by means of unbalance protection for capacitors which is properly coordinated with the operation of internal fuses in the capacitor units. It is also possible with modern protection equipment for individual components to be protected by special measurement functions such as fundamental and harmonic frequency current measurements.

## 4 Conclusion

The approach to harmonic filter design presented in this article provides a clear description of the process to be followed to ensure that compliance to emission limits is achieved, and is capable of enumerating the exact range of operating conditions and other contingencies this this compliance is valid for.

The same approach also enables the determination of the actual worst case scenario on which component ratings are determined. The approach enables the rating of equipment to be safely optimized for all actual expected operating conditions, avoiding the most unrealistic and conservative worst case conditions that are used as the basis for equipment ratings in the absence of such information.

The result is a quantified compliance test with a cost and performance optimized filter solution.

## References

[1] Technical brochure prepared by Working Group 14.30, *Guide to the specification and design evaluation Of AC filters For HVDC systems*, CIGRÉ.

[2] AS/NZS 61000-3-6:2001, *Limits — Assessment of emission limits for distorting loads in MV and HV power systems*, Standards Australia, 1999.

[3] IEEE 519-1992, *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, IEEE, 1992.

[4] AS/NZS 61000-4-7:1999, *General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*, Standards Australia, 1999.

[5] K. Debnath, “Accuracy of distribution current transformers under non-sinusoidal excitation”, in *Australasian Universities Power Engineering Conference and IEAust Electric Energy Conference*, Darwin, 26-29 September 1999.

[6] H. Seljeseth, E. A. Saethre, T. Ohnstad, and I. Lien, “Voltage transformer frequency response. measuring harmonics in norwegian 300 kv and 132 kv power systems”, in *Proceedings of the 8th International Conference on Harmonics And Quality of Power*, Trondheim, 1998.